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Terminology and Standards of Illumination*

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TERMINOLOGY and standards are subjects which give rise to unending debate. This paper, however, is intended to summarize the present status rather than to discuss debatable points or to explain details.

Language is the result of evolution; it is like a living, growing organism. We can influence its growth to a limited extent; but persistent and patient effort is necessary to bring about any important change according to plan. In technical language we wish to make each word mean the same thing at all times and to all of us. We have the double problem of defining the concepts for which names are needed and of choosing the most suitable terms for them.

The difficulty which is met in trying to hold each word to a single meaning is well illustrated by the very term "Standards." To laboratory workers the word usually means physical standards, standards of measurement. In engineering language of today, however, the term is more often used to mean an established practice or specification. Accordingly, it appears necessary to mention some standards of quality and of practice in illumination, as well as standards of measurement.

* Based on a paper under the title of "Terminology and Standards" in the Symposium on The Optics of Illumination presented at the Niagara Falls Meeting of the Optical Society of America, October 27, 1938. Published in this journal on invitation from the editor.

TERMINOLOGY OF ILLUMINATION

In the choice of technical terms and their precise definition, the Illuminating Engineering Society made an early start. That Society was formed in 1906 and very soon thereafter it appointed a Committee on Nomenclature. The subject was given considerable attention in a course of special lectures on illumination given at the Johns Hopkins University in 1910 under the auspices of the Society, and the Committee published a report during that year.

There was a considerable proportion of physicists among the members of the Society and the Committee, and their influence was very important in determining the general character of the report. Since then, the report, later designated as "Illuminating Engineering Nomenclature and Photometric Standards," has eight times been revised and expanded. The tenth edition is now approaching completion.[1]

This series of reports has had a very great influence upon terminology in this field of engineering and industry. The reports have been widely recognized as authoritative documents in legal and commercial practice, and since the establishment of the American Standards Association they have been approved as "American

[1] The report will be published in the *Transactions of the Illuminating Engineering Society*, and will also be obtainable as a separate pamphlet.

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Standards" under the procedure of the Association. The standing thus given them has its disadvantages; in particular it imposes a spirit of conservatism which tends to maintain established practices and to prevent any radical improvements.

The I.E.S. Committee has considered that its first responsibility is to the *engineering* profession; it has also recognized that it cannot dictate to the large constituency which it serves, but must make progress slowly. The Committee has therefore seldom included in its formal reports any radically new proposals. Its policy has been to encourage individual writers who have good ideas to get them into print. If the new suggestions seem to fill a need and gain a reasonable degree of acceptance on their own merits, they are then incorporated into the standard nomenclature. Such an evolution naturally affects only details or extensions of the nomenclature; it can hardly bring about changes in the fundamental ideas or the general system of terms.

For the man who writes on the subject of illumination two courses are therefore open. First, if he wants his writings to be readily understood by the great majority of technical readers, his best course is to follow the usage established in the I.E.S. Nomenclature and Standards reports. The other alternative is to be a "reformer" and develop his own system of terminology. Most reformers are nuisances to the ordinary man, but we must appreciate that improvements come about only by the efforts of those who do something different from the ordinary.

Some other publications related to the standard nomenclature of the Illuminating Engineering Society should be mentioned. A representative "sectional" committee sponsored by the American Institute of Electrical Engineers under the procedure of the American Standards Association has been working for nearly 10 years on a dictionary to be called "Definitions of Electrical Terms." A preliminary report was issued in 1932; a more comprehensive one is approaching completion, and will probably be issued within a year. It includes the terms of Illuminating Engineering as one chapter or group.

Correlation of English terms with those in other languages is being undertaken more or less independently by two organizations. The International Commission on Illumination has in course of publication a set of definitions in English, French and German to which it was planned to add terms (without the definitions) in Italian and Spanish. The date of issuance is as yet uncertain.

Another multilingual dictionary which includes illumination terms but is less authoritative in this field has just been issued by the International Electrotechnical Commission. It has definitions in French and English and terms without definitions in German, Italian, Spanish and Esperanto.

A comprehensive nomenclature of illumination necessarily runs over into border regions where the authority of the illuminating engineers might be questioned. For example, in the present revision of the I.E.S. nomenclature a section on radiation is included. The nomenclature has also included previously a short section on color, and this is being expanded somewhat in the present revision. In this particular field, however, the greater competency of the Committee on Colorimetry of the Optical Society is recognized, and for detailed and precise application of the terms reference will be made to the prospective report of that Committee.[2]

In the field of radiation, definitions of terms are included in the treatise on *Measurement of Radiant Energy* prepared under the direction of a committee of the National Research Council and edited by W. E. Forsythe. A source of general information regarding terms in physics is the *Glossary of Physics* compiled by L. D. Weld.

In the field of illumination itself, a bolder venture is represented by P. H. Moon's textbook, *The Scientific Basis of Illuminating Engineering*. Professor Moon's teaching work has led him to make a critical analysis of the accepted terminology and he finds its deficiencies serious enough to justify an attempt at radical reform. Whether or not one agrees entirely with him, the book can be commended as a careful presentation of a logical system of nomenclature.

Standards of Measurement

The physical standards on which all measurements in illumination are now based are decidedly

[2] See preliminary draft of report on nomenclature and definitions by Loyd A. Jones, J. Opt. Soc. Am. **27**, 207–213 (1937).

unsatisfactory in theory and yet the system of practical standards which has been built up has served so well that relatively few people realize the need for anything better. While the historical bases are diverse, the practical working standards almost invariably used for measurements of precision are electric incandescent lamps. Historically the values assigned to these standards go back to flame standards, usually candles of various kinds. Consequently we have still the name "candle" for the unit of intensity.

Since measurement of light is really an evaluation of the visual effects of radiant energy, the simple theoretical solution for the problem of standards of light would be to establish an accepted relation between radiant energy and light, or between radiant flux and light flux. In fact, however, there is not sufficient certainty in the absolute measurement of radiant energy to make that solution of the problem acceptable at the present time. On the other hand, our knowledge of the behavior of radiating bodies, and in particular the blackbody, has been carried to a relatively high state of perfection. For many years, therefore, it has been anticipated that the blackbody would eventually be adopted as the basis for measurements of light. A point which has not been so generally understood is that for practical purposes such a basic physical standard is not sufficient, for we must have also an accepted means of deriving from it a whole system of standards. This is necessary because the visual effects of radiant energy, of course, depend very greatly upon wave-length or frequency and the practical sources of light give widely different distributions of energy through the spectrum, with correspondingly different colors.

The solution of this problem which has already been accepted in principle is the adoption of the blackbody at the freezing point of platinum as the fundamental standard and the agreement that sources giving light of color different from that of the blackbody shall have their photometric values assigned in accordance with relative spectral luminosity factors which have been adopted by the International Commission on Illumination and the International Committee on Weights and Measures.

The first idea was that the blackbody at the freezing point of platinum would be used simply as a permanent custodian of the old unit known as the international candle. Accordingly, Wensel, Roeser, Barbrow and Caldwell[3] determined the brightness of the blackbody standard in international candles, finding the value 58.84. This value has been checked fairly closely in laboratories in England, France and Germany, so that the rounded value 58.9 is rather generally accepted. Such a perpetuation of the international candle, however, would leave two units in use, that is, the international candle and the Hefner unit. As a means of clearing up this difficulty it was suggested by the National Bureau of Standards that both of the old basic units be abandoned and that a new one be established, its magnitude being fixed by taking the brightness of the blackbody at the platinum point as exactly 60 candles per cm^2. This proposal has been accepted by all countries concerned except that up to the present time the Japanese have refrained from voting on it.

The International Committee on Weights and Measures arranged to have lamps of several types calibrated according to the new scale by various national laboratories and brought together by April, 1938, at the National Physical Laboratory of Great Britain for comparison, so that any discrepancies between countries might be adjusted before the new units were introduced into practice. Lamps from the National Bureau of Standards were sent in accordance with the plan, and those from the Physikalisch-Technische Reichsanstalt at Berlin have recently been supplied. Presumably, therefore, comparisons are being made between three sets of standards. Unfortunately, these comparisons do not include any standards operating at temperatures as high as those of gas-filled tungsten lamps, but if the standards at lower temperatures are found to be in good agreement, the step to gas-filled lamps can be made without great difficulty. The step from the platinum point to vacuum tungsten lamps has been made by using blue filters for which the transmission has been determined by

[3] H. T. Wensel, W. F. Roeser, L. E. Barbrow and F. R. Caldwell, Nat. Bur. Stand. J. Research **6**, 1103–1117 (1931). Research Paper 325.

use of the standard luminosity factors. The same filters are used to make the second step from vacuum to gas-filled lamps. The values for gas-filled lamps can also be checked by direct measurement against a blackbody operated at the freezing point of iridium,[4] and all the measurements can be checked by a physical photometer having a spectral sensitivity closely the same as that of the "standard eye" represented by the luminosity factors.[5] There are, therefore, three independent methods of checking the standards at higher temperature. Consequently, it is expected that standards on the new basis can be distributed soon by the national laboratories. The date set for use of the new units in practice is January 1, 1940.

During the last year a question affecting the plan has been raised by the German National Committee of the International Commission on Illumination. The German Committee recommends that the values of the luminosity factors be reconsidered on the ground that the present factors do not represent the sensitivity of the eye under conditions of pure cone vision. A redetermination of the factors made with a flicker photometer by Paul Jainski at the Technische Hochschule in Charlottenburg, with a small field of view (1.2°) and very high brightness (200 to 800 apostilbs, or approximately 20 to 80 footcandles on a white surface), confirms the previous German opinion that under these conditions the luminosity curve should be shifted toward the red as compared with the standard curve. It is fairly certain that other countries will not wish to agree to such a change of the luminosity curve, since it would introduce confusion into a great many applications which have been made of the old factors, and furthermore would put the evaluation of lights on a basis very different from any conditions of use. It remains to be seen whether the German Committee will insist on an adjustment of the factors as a condition for carrying out the agreement to accept the new system of units.

[4] H. T. Wensel, W. F. Roeser, L. E. Barbrow and F. R. Caldwell, Nat. Bur. Stand. J. Research **13**, 161–168 (1934), and more recent unpublished work.

[5] K. S. Gibson, R. P. Teele and H. J. Keegan, Paper No. 21 at this meeting of the Optical Society of America.

Standard Specifications of Quality of Lamps and Appliances

In the field of engineering or commercial "standards" the specifications for quality of incandescent lamps are well established. The principal manufacturers of incandescent lamps, in collaboration with some large users and testing agencies, have developed specifications covering in great detail the methods of test and the performance required of incandescent lamps. These specifications are available to the public in the form of Federal Specification W-L-101, the current edition being W-L-101c.[6] Supplements issued each year give the specified numerical values for performance of different sizes of lamps. The changes from year to year are generally increases in the required efficiencies of production of light, intended to maintain a uniform rated life, which is 1000 hours for most sizes of lamps, and 750 hours for some of the intermediate sizes.

For fixtures and other appliances in which incandescent lamps are used, there are not such definite specifications because there is necessarily much greater diversity in such devices, and performance cannot be so definitely prescribed. The Illuminating Engineering Society, however, has issued specifications for the testing of appliances of certain types. It has also developed quite definite specifications for study lamps, of both desk and floor types; "I.E.S." study lamps certified by authorized testing laboratories as complying with these specifications have been sold to the number of more than a million.

Standards of Practice in Illumination

In the specification of amount and character of illumination required for different purposes one can hardly say that standards have been established. Extensive investigations have been made in the attempt to determine the amount of illumination necessary for most efficient work, but in general these have been inconclusive because there is no satisfactory method of determining the "efficiency" of human beings. So far as amount of product is concerned, workers seem

[6] Obtainable from the Superintendent of Documents, Government Printing Office, Washington, D. C., at 5 cents each for specification and for supplements.

to do very well with a moderate illumination. For example, careful tests made by the Public Health Service in postoffice workrooms indicated that an illumination of eight footcandles gave as good results, with regard to amount and accuracy of work, as much greater illuminations. Somewhat similar results have been obtained in various tests carried out by the Department of Scientific and Industrial Research of Great Britain. It is argued, however, that in these tests no account was taken of the fatigue of workers or of the possible effects of long continued work.

Any such tests, in order to be conclusive, must include studies of many workers and involve considerable expense. It is extremely difficult to carry out such tests without changing conditions in such a way that workers will be affected by their knowledge of the experiment. When the workers know that experiments are being made, prejudices and other psychological conditions may readily overshadow entirely any direct effects of variation in the amount of illumination.

Furthermore, it must be recognized that the part played by detailed vision in industrial operations varies greatly. Many operations can be carried on by experienced workers with extremely small amounts of light, while other operations require good illumination. Recognizing this fact, the Committee on Industrial Lighting of the Illuminating Engineering Society has in recent years made very detailed studies of the amount of light required not merely in different industries but for different operations and even on different parts of the same machine. As a result of these studies there is being prepared a series of reports which are an approach to "standards" for lighting in the particular industries and under the working conditions studied. Under the general title "Researches on Industrial Lighting" such reports have been published in the Transactions of the I.E.S. for 1936, 1937 and 1938 on the following industries: printing; textiles (gray goods and denim, and silk and rayon throwing and wide goods weaving); shoe manufacturing; candy manufacturing; intricate production, assembly and inspection processes. These reports, as well as the codes mentioned below, are also obtainable in separate pamphlets.

Recommended practices in several types of lighting have been compiled by committees of the I.E.S. These include a *Code of Street Lighting* (1930), *Code of Highway Lighting* (1936), *Code of Lighting for Factories, Mills and other Work Places* (1930), and *Recommended Practice of School Lighting* (1938). The last two were developed under the procedure of the American Standards Association and have been approved by the A.S.A. A number of the States have regulations on lighting in industrial plants, but such legal requirements must in general be limited to the specification of minimum illumination and other conditions necessary for safety. Information on such regulations has been compiled in Bulletin No. 94[7] of the Women's Bureau, Department of Labor, *State Requirements for Industrial Lighting* (1932). Legal establishment of *minimum* values of illumination in work places has also received much attention in Great Britain, and governmental Committees on Lighting in Factories have issued several reports.[8]

Such specifications of *minimum* values of illumination allowable have little relation to the question of determining how much illumination is desirable or most economical in a broad sense. The values recommended in the Codes mentioned above are usually many times the minium requirements. It is difficult to prove conclusively how much light is really needed, but even the amounts of illumination recommended are small in comparison with those under which man ordinarily works when natural light is used in the open. Consequently, even though it is difficult to show definitely any advantage of using relatively large amounts of artificial illumination, one must hesitate to say that a meager amount will have no detrimental effect on those who work under it for long periods.

[7] Obtainable from the Superintendent of Documents, Government Printing Office, Washington, D. C., for 10 cents.

[8] The latest (November, 1938) can be obtained from His Majesty's Stationery Office, London, for 1s, plus postage, or from the British Library of Information, 620 Fifth Avenue, New York.

Basic Principles in Illumination Calculations*

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(Received January 5, 1939)

THE illuminating engineer is interested in calculating and measuring *amounts of radiant energy:* the amount, in certain wave-length bands, radiated by lamps; the amount in projector beams; the amount incident on the surfaces of desks and other objects; the variations in amount that give shadows and glare. The dimensions of his equipment are so large that diffraction effects are rarely of importance; and his work can be based, in most cases, on geometrical optics rather than physical optics.

One might expect that the illuminating engineer would find a satisfactory and rigorous basis for his calculations in the standard treatises on geometrical optics. But such is not the case. With the exception of Herman's book,[1] works on geometrical optics contain little or nothing that can be used by the engineer. As a result, he has continued to employ the methods of Lambert,[2] methods which were excellent in 1760 but which are thoroughly out of step with 19th- and 20th-century physics.

It would be natural to expect the 18th-century methods of illumination calculation to develop with the advance of optics and to keep their place as an important branch of optical theory, but this development did not take place. One reason was the lack, until recently, of stimulus for such development. The practical need for illumination calculations had to await the advent of light sources of high efficacy and high power. Today, however, electric lamps can compete economically with daylight in the lighting of buildings; the *engineering* of lighting becomes daily more important; and the lighting expert finds himself hampered continually by inadequate theory, based on antiquated concepts and utterly devoid of generality.

To meet modern needs in the calculation of amounts of radiant energy, a number of investigators are now applying field theory to the subject and have developed a *theory of the light field*, somewhat analogous to the well-established theory of the electric field. It should be realized that this theory of the light field is entirely distinct from Maxwell's electromagnetic field theory and is a branch of geometrical optics, not physical optics. Noteworthy in the new movement are Herman,[1] Hyde,[3] Fock,[4] Yamauti,[5] Gershun,[6] Gurevitch,[7] and Boldyrev.[8] The theory of the light field, like any other new theory, needs development; and I hope that the following résumé will stimulate further advances in the subject.

2. PHOTOMETRIC CONCEPTS

The basic concept of any modern illumination theory is *radiant energy*, not candlepower. On this foundation, one can build up a system of radiometric concepts[9] related to each other geometrically, as few or as many as one wishes. An analogous set of photometric concepts can be obtained from the radiometric by evaluating

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[1] R. A. Herman, *Treatise on Geometrical Optics* (Cambridge University Press, 1900).

[2] J. H. Lambert, *Photometria siva de mensura et gradibus luminis, colorum et umbrae* (1760).

[3] E. P. Hyde, "Geometrical Theory of Radiating Surfaces," Nat. Bur. Standards Bulletin **3**, 81 (1907).

[4] V. Fock, "Zur Berechnung der Beleuchtungsstärke," Zeits. f. Physik **38**, 102 (1924). Trans. Opt. Inst., Leningrad **3**, No. 28 (1924).

[5] Z. Yamauti, *Theory of Field of Illumination*, Res. Elec. Lab., Tokyo, Japan, No. 339 (1932).

[6] A. Gershun, *The Light Field* (in Russian), (Moscow, 1936). Translated by P. Moon and G. Timoshenko and accepted for publication in J. Math. Phys. (1939). A. Gershun, "Notions du champ lumineux et son application à la photométrie," R. G. E. **42**, 5 (1937). A. Gershun, "Sur une théorie du champ lumineux," R. G. E. **44**, 307 (1938).

[7] A. Gershun and M. M. Gurevitch, "The Light Field" (in Russian), J. Russ. Phys.-Chem. Ges., Phys. Abt. **60**, 355 (1928). M. M. Gurevitch, "Eine Vektordarstellung der photometrischen Grössen," Physik. Zeits. **30**, 640 (1929). Trans. Opt. Inst., Leningrad **5**, No. 44 (1929).

[8] N. G. Boldyrev, "On the Light Field in Scattering Media," (in Russian), Trans. Opt. Inst., Leningrad **6**, No. 59 (1931).

[9] Parry Moon, *Scientific Basis of Illuminating Engineering* (McGraw-Hill, 1936), p. 546.

each with respect to the standard lamprosity[10–12] function for the eye. In the following treatment the photometric names will be used, but everything applies equally well to the radiometric concepts.

Three concepts will be introduced. More may be used if desired, but three seems to be a practical minimum.

(1) The first is *luminous flux F:* the flux of radiant energy evaluated with respect to the standard lamprosity function. The concept of luminous flux is firmly established,[13] but the other two concepts must be defined in a somewhat more general manner than is customary, in order to fit them for vector field treatment.

(2) *The flux density vector* **D** at any point P is a vector pointing in the direction of the maximum net flow of radiant energy and having a magnitude equal to this maximum net radiant flux per unit area, evaluated with respect to the lamprosity function.[6, 14] Evidently, **D** is a generalization of the common concept, *illumination*, which is here divorced from the idea of an illuminated plane.

(3) *Selance B* at any point P and in a specified direction is defined by the relation:

$$B = \lim_{\omega \to 0} \frac{D}{\omega}, \qquad (1)$$

where D = magnitude of the luminous flux density vector at P (lumen meter^{-2}); ω = solid angle, with its axis in the specified direction and with its apex at P. B may be measured in lumen m^{-2} steradian^{-1}.

One can imagine the measurement of B to be done as indicated in Fig. 1. A small barrier-layer photo-cell is mounted at the end of a blackened tube. The cell is placed at the point P where B is to be measured and the tube is oriented so that its axis is in the desired direction. The solid angle ω is now reduced, and readings are taken of luminous flux density *vs.* solid angle. The ratio, as $\omega \to 0$, is defined as the selance B at the specified point and in the specified direction.

Evidently, selance is a generalization of the ordinary concept of brightness. Brightness is usually considered as a quantitative attribute of a definite luminous surface and is expressed in candles per unit of projected area of that surface. This narrow definition, however, may lead to confusion if the source is not a surface but a volume, or if source and observer are separated by an absorbing and scattering medium. The definition given by Eq. (1) seems preferable because of its generality. But the word "brightness" is used in so many different senses[15] that it is advisable to coin a new word to represent the generalized concept of Eq. (1). The word *selance* is suggested (σέλας = brightness. Applied to flames, etc.).

3. Elements of Field Theory

The older idea of luminous flux density on definite surfaces is now replaced by the more general idea of a light field, at each point of which there is a vector **D**. It is a commonplace that a field is completely specified in a given region if the curl and the divergence are known at each point of that region and if boundary conditions and discontinuities are specified. Thus it is advisable to consider div **D** and curl **D**.

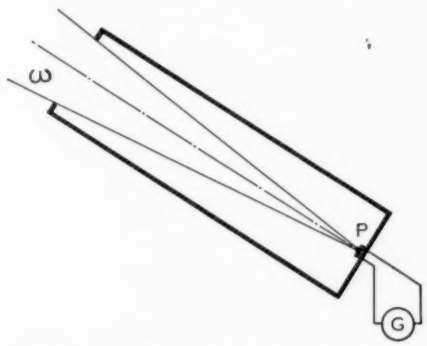

Fig. 1. A photoelectric brightness meter.

[10] Called "visibility," "luminosity," etc. by various writers. The usual names have so many different meanings and result in so much confusion that it seems advisable to introduce a new word to represent this one specific thing—the curve based upon the visual research of Gibson and Tyndall (reference 11) and tabulated for intervals of 0.001μ by Judd (reference 12). The word *lamprosity* (from the Greek λαμπρός, a word often used in referring to the luminosity of colors) is suggested.

[11] K. S. Gibson and E. P. T. Tyndall, "The Visibility of Radiant Energy," Nat. Bur. Standards Bulletin **19**, 131 (1923).

[12] D. B. Judd, "Extension of the Standard Visibility Function to Intervals of 1 millimicron," Nat. Bur. Stand. J. Research **6**, 465 (1931).

[13] *Illuminating Engineering Nomenclature and Photometric Standards.* (Illuminating Engineering Society, New York).

[14] Reference 9, p. 304.

[15] Reference 9, p. 556.

From the definition of divergence, one can say immediately that

$$\text{div } \mathbf{D}=0 \tag{2}$$

in all regions of space where there are no sources of radiation and where there is no absorbing matter. The absorption of radiant energy by air is usually negligible with distances of 100 meters or less; and even in fog, div **D** can ordinarily be considered zero. Thus, except in the interiors of lamps, the light field of the vast majority of engineering applications is a *solenoidal field.* Tubes of flux may be used, with the same flux through any section of a given tube.

A simple example, whose solution is tedious by the method of surface integration, is given by Gershun.[6] What is the luminous flux from the sphere to the circular disk of Fig. 2? The sphere is assumed to be such that the selance B is constant from every point of the disk. Obviously, at any point in space the **D**-vector is directed radially from the center of the sphere and indicates the direction of maximum flow of radiant energy. Tubes of flux will have the shape of truncated cones with apices at the center of the sphere. In particular, consider the tube of flux formed by the right circular cone whose base is the circular disk. The flux from the portion of the sphere enclosed by this cone is

$$F=\pi B\cdot(\text{area})=\pi B\omega a^2.$$

But div **D**=0, so the flux is the same throughout the tube. Thus the flux on the disk is

$$F=\pi B\omega a^2=2\pi^2a^2B(1-\cos\ \gamma_1). \tag{3}$$

If both div **D** and curl **D** were zero, the light field would be an exact analog of the electrostatic field. Unfortunately, curl **D** is generally not zero. For curl **D** to be zero, the line integral:

$$\oint \mathbf{D}\cdot d\mathbf{s}=0$$

around any small closed path at P must be zero. Evidently, this condition is satisfied for every point in the field produced by a small *uniform* source; but most sources do not give a uniform light distribution, in which case curl **D**$\neq$0. This fact explains the startling similarity sometimes noticed between illumination calculations and electrostatic calculations, a similarity that breaks down, however, in more complicated problems. A failure to understand this fact has led to attempts to use an *illumination potential* in cases where no potential exists.[16]

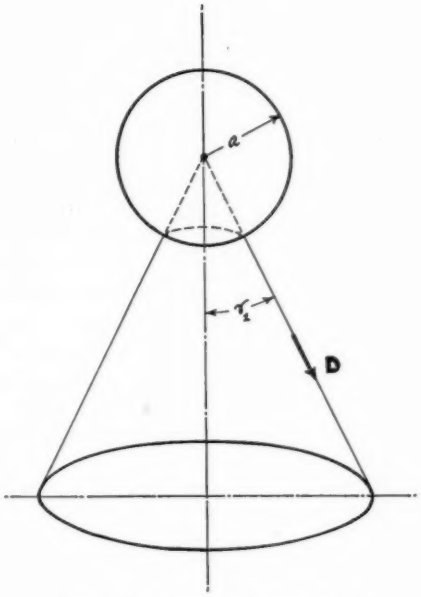

FIG. 2. Flux from a sphere to a disk.

The necessary and sufficient condition for the existence of a scalar potential φ is that curl **D** be zero. Then

$$\mathbf{D}=-\text{grad } \varphi \tag{4}$$

and a set of equipotential surfaces exist and are everywhere orthogonal to the flux lines. Then, too, Laplace's equation:

$$\nabla^2\varphi=0$$

can be used to obtain the illumination potential φ for specified boundary conditions, after which **D** may be obtained by use of Eq. (4). The method is of very limited applicability, however, because of the small number of light fields that are irrotational. The field produced by one or more uniform spherical sources is irrotational, as is the field from those gaseous discharge lamps in which absorption of radiation is negligible. But fields produced by sodium-vapor lamps, for instance, are not irrotational, nor are fields produced by plane, perfectly diffusing surfaces.

[16] B. Jones, "The Mathematical Theory of Finite Surface Light Sources." Trans. I. E. S. **5**, 281 (1910).

Even though a scalar potential does not exist, there may be a set of surfaces orthogonal to the flux lines. The condition for the existence of such surfaces is[17]

$$\mathbf{D}\cdot\text{curl }\mathbf{D}=0 \tag{6}$$

and a quasi-potential φ' is then said to exist. The use of the quasi-potential has been treated by Yamauti.[5]

Another idea is that of the *vector potential*. If the field is solenoidal, a vector potential **A** may be introduced, such that

$$\mathbf{D}=\text{curl }\mathbf{A}. \tag{7}$$

The vector potential appears to have been first applied to illumination theory by Herman[1] and has been used with considerable success by Fock.[4]

4. Methods of Calculating D

One of the practical applications of the theory of the light field is the calculation of the luminous flux density on various surfaces. This requires merely an expression for **D**; for if **D** is known at a given point in space, then the scalar flux density at that point, on a surface oriented in any way, is

$$E=D\cos\theta=\mathbf{D}\cdot\mathbf{N}_1 \tag{8}$$

where θ=angle between **D** and the inward-drawn unit normal $\mathbf{N}_1$ for the surface. The calculation of **D** may be effected in five ways:

(1) The classical method of surface integration

An expression is obtained for the luminous flux density produced at an arbitrary point on an arbitrary surface by an element $d\sigma$ of luminous surface. A double integration over the surface of the source then gives the desired flux density. Since the integrations are often very troublesome, even in comparatively simple cases, the method of surface integration is undoubtedly the most arduous and time-consuming of all the methods and should be abandoned.

(2) Solid-angle method

From the definition of selance, Eq. (1),

$$d\mathbf{D}=Bd\boldsymbol{\omega},$$

which is the flux density vector produced by the luminous flux through the infinitesimal light cone $d\omega$. The vector $d\boldsymbol{\omega}$ is directed along the axis of the light cone toward its vertex. If radiant energy is received at P through a solid angle ω (Fig. 3) the resulting **D** is

$$\mathbf{D}=\int_\omega Bd\boldsymbol{\omega}. \tag{9}$$

Eq. (9) constitutes one of the most powerful and most useful relations in lighting calculations. It is not new, having been employed extensively for some time.[18] It is often called the "unit-sphere method." It is considered here because it follows so directly from the new definition of B instead of being developed in the ordinary artificial and round-about way. Noteworthy is the generality of Eq. (9), which applies without subterfuge to "point" sources, surface sources of uniform or non-uniform characteristics, volume sources, as well as to light received through diffusing and absorbing media such as fog and smoke. In all cases, the selance B is obtained at the point P, not at the source, and thus includes the effects of any media interposed between the sources and P. In the special case of a transparent and homogeneous medium, the selance at P becomes equivalent to the customary concept of brightness of the source.

(3) The plane-angle method

This method has been used by Fock,[4] Gershun,[6] Yamauti,[5] and others. It is less general than the solid-angle method but is often useful, particularly when the light cone degenerates into a pyramid. If B=const. for all angles in which light is being received at P, then

$$\mathbf{D}=B\int_\omega d\boldsymbol{\omega},$$

which, from geometrical considerations,[19] is equal to

$$\mathbf{D}=\frac{B}{2}\int_\alpha d\boldsymbol{\alpha}, \tag{10}$$

where $d\boldsymbol{\alpha}$ is a vector which is normal to the surface of the convergent light cone (Fig. 4) and

[17] H. B. Phillips, *Vector Analysis* (John Wiley and Sons, New York, 1933), p. 102.

[18] J. Dourgnon, "Eléments théoriques de la photométrie," R. G. E. **41**, 619 (1937).

[19] Reference 6, p. 145.

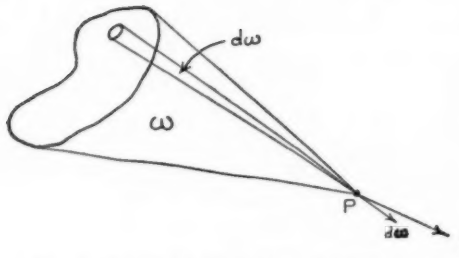

FIG. 3. The solid-angle method of calculating **D**.

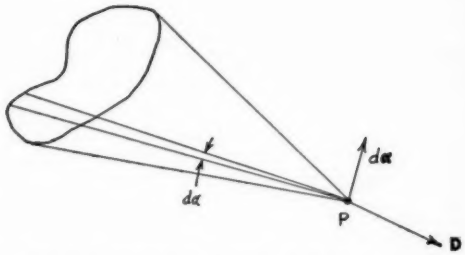

FIG. 4. The plane-angle method of calculating **D**.

whose magnitude is equal to the plane angle $d\alpha$ on the surface of the cone. Fock[4] determined Eq. (10) on the basis of a contour integral around the source, but it seems more general to confine attention to conditions at the point P, as has been done by Gershun.[19]

If the light cone degenerates into a pyramid of n sides, all the $d\boldsymbol{\alpha}$-vectors for a given side add directly to form a vector $\boldsymbol{\alpha}_i$, whose magnitude is equal to the apex angle for that side of the pyramid. Then Eq. (10) becomes

$$\mathbf{D}=\frac{B}{2}\sum_{1}^{n}\boldsymbol{\alpha}_i. \tag{11}$$

(4) Field mapping, potential and quasi-potential

The plane-angle method appears to be a recent development which would not have appeared without the stimulus of the vector-field idea. Another method, even more closely related to the engineering treatment of other fields, is the mapping of the light field. If div $\mathbf{D}=0$, tubes of flux exist. Flux lines can be determined by any of the usual graphical or analytical methods, and a measurement of the distance between lines can be used in obtaining a quantitative measure of the flux density on any surface at any point in the light field.

An example is shown in Fig. 5. The flux tubes from a uniformly luminous, perfectly diffusing circular disk source in a transparent, homogeneous medium are bounded by confocal hyperboloids of one sheet, and planes that contain the axis of symmetry.[20] The distance between hyperboloids may be adjusted so that each tube transmits the same flux. Then the flux density, at any point P on an arbitrarily oriented surface SS is

$$E=\pi Bl_1r_2/l_2r_1, \tag{12}$$

where l_1, l_2, r_1 and r_2 are measured from the map.

This method can be applied whenever div $\mathbf{D}=0$, irrespective of the existence of a scalar potential. In the special cases where a scalar potential φ exists, all the well-established results of potential theory can be applied to the light field. When a potential does not exist, it may be advisable to consider the quasi-potential φ', which exists in all two-dimensional solenoidal fields and in all solenoidal fields having axial symmetry.

(5) The vector potential

If div $\mathbf{D}=0$, a vector potential $\mathbf{A}$ exists and

$$\mathbf{D}=\text{curl }\mathbf{A}. \tag{13}$$

Fock[4] has shown that if the source has uniformly luminous, perfectly diffusing surfaces,

$$\mathbf{A}=-\frac{B}{2}\oint \ln r\, d\mathbf{s}, \tag{14}$$

where the integral is taken around the contour of the source and where r is the magnitude of the distance from P to the element ds of the contour.

The method requires a single integration, followed by differentiation, Eq. (13), the latter being performed always without difficulty. For a plane source, there is a slight advantage over the plane-angle method because the $d\mathbf{A}$-vectors are in the plane of the source instead of sticking out in space as the $d\boldsymbol{\alpha}$-vectors do; but this advantage is probably more than balanced by the work required in the integration. The principal use of the vector potential is in the calculation of total flux rather than flux density.

[20] Reference 6, p. 110.

5. Methods of Calculating Total Flux

Another use for the theory of the light field is in calculating the total flux from one surface or aperture to another. There are three methods:

(1) Classical method of surface integration

An equation is derived for the flux density at any point on the receiving surface, after which a double integration over this surface gives total flux. In most practical cases, the quadruple integration is almost hopelessly complicated.

(2) Field mapping

If a map has been obtained for the field, the total flux is easily evaluated, as noted in Section 3.

(3) Vector-potential method

The vector potential **A** is first obtained (Section 4), after which a single integration gives total flux:

$$F = \int_{C2} \mathbf{A} \cdot d\mathbf{s}_2, \tag{15}$$

where $d\mathbf{s}_2$ is an element of the contour C_2 of the receiving surface and **A** is the vector potential on C_2.

6. Example, the Rectangular Source

As an example of the calculation of flux density by various methods, consider a rectangular source (Fig. 6) which has a perfectly diffusing, uniformly luminous surface and which is in a transparent, homogeneous medium. The flux density is desired at P on a surface oriented at any arbitrary angle. The solution is well known and the problem is introduced here merely to indicate the relative difficulties attending the solution by various methods.

Direct surface integration has been used, notably by Yamauti[21] and by Higbie,[22] but the result is obtained only after an arduous struggle. The *solid-angle method* requires the evaluation of the integral:

$$\mathbf{D} = B \int_{\omega} d\omega,$$

which can be effected in several ways. Probably the simplest is by use of a sphere of unit radius and the projection, onto three mutually per-

[21] Z. Yamauti, *Geometrical Calculation of Illumination*, Res. Electrotech. Lab., Tokyo, No. 148 (1924).

[22] H. H. Higbie, *Lighting Calculations* (John Wiley and Sons, 1934), p. 165.

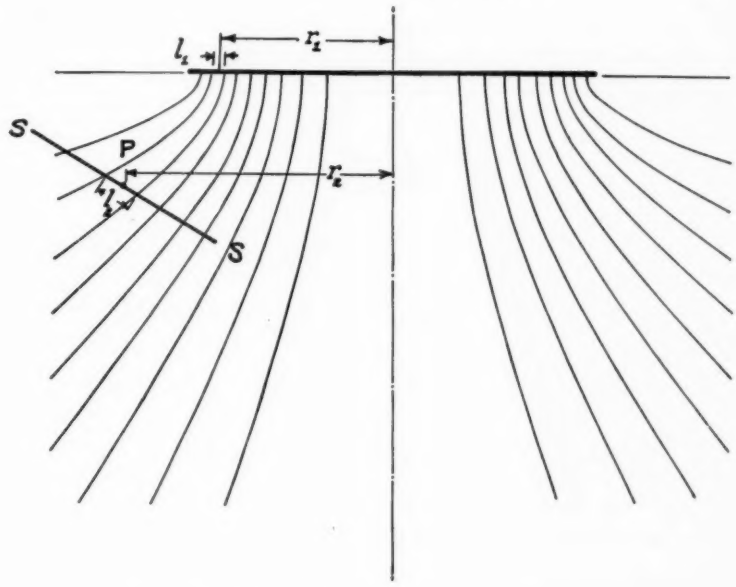

Fig. 5. The light field from a uniform circular disk source.

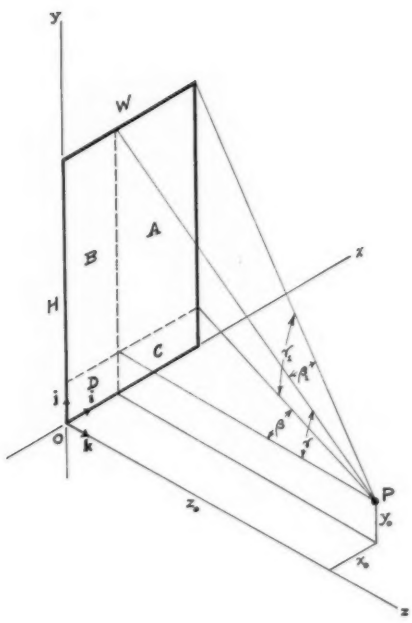

FIG. 6. A rectangular source.

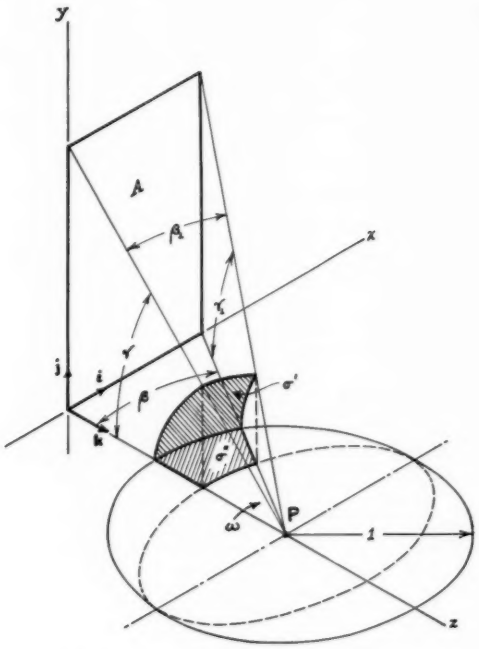

FIG. 7. The solid-angle method applied to the rectangular source.

pendicular planes, of the area cut from the sphere by the light cone. The general case of Fig. 6 is obviously reducible to four simple sources (A, B, C and D) with P on a perpendicular erected at the common corner of the sources. Thus in Fig. 7 one need consider only one of these sources, as A.

The solid angle ω is equal to the area σ' cut from the sphere by a horizontal plane, two vertical planes through the sides of the source, and a plane determined by the top of the source and P. The projection of the area σ' on the xz plane determines the y component of the **D**-vector, which by simple geometry is

$$D_y = B\sigma'' = \frac{B}{2}[\beta - \beta_1 \cos\gamma]. \tag{16}$$

The other two components are found similarly by projecting σ' onto the xy and yz planes. Thus **D** is written down directly by the use of elementary geometry and without the necessity of any integration.

$$\mathbf{D} = \mathbf{i}D_x + \mathbf{j}D_y + \mathbf{k}D_z, \tag{17}$$

where

$$\left.\begin{aligned} D_x &= -\frac{B}{2}[\gamma - \gamma_1 \cos\beta], \\ D_y &= -\frac{B}{2}[\beta - \beta_1 \cos\gamma], \\ D_z &= \frac{B}{2}[\beta_1 \sin\gamma + \gamma_1 \sin\beta]. \end{aligned}\right\} \tag{18}$$

The negative signs in Eq. (18) result from the choice of positive directions of x and y (Fig. 7). The scalar flux density at P on an arbitrary oriented surface is

$$E = D\cos\theta, \tag{8}$$

where θ = angle between **D** and $\mathbf{N}_1$. Or,

$$E = D_x\lambda + D_y\mu + D_z\nu, \tag{19}$$

where λ, μ and ν are the direction cosines of $\mathbf{N}_1$. The *plane-angle method* employs the equation:

$$\mathbf{D} = \frac{B}{2}\sum_1^4 \boldsymbol{\alpha}_i, \tag{20}$$

where $\alpha_1=\gamma$, $\alpha_2=\beta$, $\alpha_3=\gamma_1$, and $\alpha_4=\beta_1$ (Fig. 7). The $\boldsymbol{\alpha}_1$-vector is normal to the plane determined by the left side of the source and P, the $\boldsymbol{\alpha}_2$-vector is in the y direction, etc.[23] Thus the result is written down immediately:

$$\mathbf{D}=\frac{B}{2}\{-\mathbf{i}(\gamma-\gamma_1\cos\beta)-\mathbf{j}(\beta-\beta_1\cos\gamma)+\mathbf{k}(\beta_1\sin\gamma+\gamma_1\sin\beta)\}. \quad (21)$$

The *method of field mapping* is not well adapted to this problem because of lack of symmetry. However, in the related problem of a rectangular source extending for great distances on both sides of the yz plane, such as would be approximated by a long row of windows in a factory, the problem becomes a two-dimensional one and a map similar to Fig. 5 can be used.[3] The scalar flux density on any surface is then obtained by measurement on the map, since

$$E=\pi B\frac{l_2}{l_1}. \quad (22)$$

The *vector-potential method* requires the calculation of A:

$$\mathbf{A}=-\frac{B}{2}\oint \ln r\, d\mathbf{s}. \quad (14)$$

For the bottom of the source (Fig. 6),

$$r^2=z_0^2+y_0^2+(x-x_0)^2$$

and

$$A_x=-\frac{B}{4}\int_{-x_0}^{W-x_0}\ln[(z_0^2+y_0^2)+\xi^2]d\xi,$$

where $\xi=x-x_0$. Integration gives, for this side alone,

$$A_x=\frac{B}{4}\Big\{-(W-x_0)\ln[z_0^2+y_0^2+(W-x_0)^2]-x_0\ln[z_0^2+y_0^2+x_0^2]+2W-2(z_0^2+y_0^2)^{\frac{1}{2}}\times\left[\tan^{-1}\frac{W-x_0}{(z_0^2+y_0^2)^{\frac{1}{2}}}+\tan^{-1}\frac{x_0}{(x_0^2+y_0^2)^{\frac{1}{2}}}\right]\Big\}.$$

Similar integrations for the other sides give the final components of **A** as

$$A_x=\frac{B}{2}\Big\{\left(\frac{W-x_0}{2}\right)[\ln[z_0^2+(H-y_0)^2+(W-x_0)^2]-\ln[z_0^2+y_0^2+(W-x_0)^2]]+\frac{x_0}{2}[\ln[z_0^2+(H-y_0)^2+x_0^2]-\ln(z_0^2+x_0^2+y_0^2)]-(z_0^2+y_0^2)^{\frac{1}{2}}\times\left[\tan^{-1}\frac{W-x_0}{(z_0^2+y_0^2)^{\frac{1}{2}}}+\tan^{-1}\frac{x_0}{(z_0^2+y_0^2)^{\frac{1}{2}}}\right]+(z_0^2+(H-y_0)^2)^{\frac{1}{2}}\left[\tan^{-1}\frac{W-x_0}{(z_0^2+(H-y_0^2))^{\frac{1}{2}}}+\tan^{-1}\frac{x_0}{(z_0^2+(H-y_0)^2)^{\frac{1}{2}}}\right]\Big\}, \quad (23)$$

$$A_y=\frac{B}{2}\Big\{\frac{(H-y_0)}{2}[\ln[z_0^2+x_0^2+(H-y_0)^2]-\ln[z_0^2+(W-x_0)^2+(H-y_0)^2]]+\frac{y_0}{2}[\ln[z_0^2+x_0^2+y_0^2]-\ln[z_0^2+(W-x_0)^2+y_0^2]]-(z_0^2+(W-x_0)^2)^{\frac{1}{2}}\left[\tan^{-1}\frac{H-y_0}{(z_0^2+(W-x_0)^2)^{\frac{1}{2}}}+\tan^{-1}\frac{y_0}{(z_0^2+(W-x_0)^2)^{\frac{1}{2}}}\right]+(z_0^2+x_0^2)^{\frac{1}{2}}\left[\tan^{-1}\frac{H-y_0}{(z_0^2+x_0^2)^{\frac{1}{2}}}+\tan^{-1}\frac{y_0}{(z_0^2+x_0^2)^{\frac{1}{2}}}\right]\Big\}, \quad (24)$$

$$A_z=0. \quad (25)$$

The **D**-vector is now obtained by differentiation of (23), (24) and (25), according to the relation:

$$\mathbf{D}=\text{curl }\mathbf{A}=\mathbf{i}\left[\frac{\partial A_z}{\partial y_0}-\frac{\partial A_y}{\partial z_0}\right]+\mathbf{j}\left[\frac{\partial A_x}{\partial z_0}-\frac{\partial A_z}{\partial x_0}\right]+\mathbf{k}\left[\frac{\partial A_y}{\partial x_0}-\frac{\partial A_x}{\partial y_0}\right]. \quad (26)$$

[23] Reference 9, p. 312.

Since $A_z=0$,

$$D_x=-\frac{\partial A_y}{\partial z_0}, \quad D_y=\frac{\partial A_x}{\partial z_0}, \quad D_z=\frac{\partial A_y}{\partial x_0}-\frac{\partial A_x}{\partial y_0} \tag{27}$$

and, when $x_0=y_0=0$, **D** is found to be the same as obtained in Eqs. (17) and (18).

7. Conclusions

The theory used by illuminating engineers today is thoroughly antiquated and makes no use of the field concept which has proved to be so valuable in other branches of physics. The old theory lacks generality: Ordinarily, its exposition begins with a consideration of that fictitious entity, the "point" source. Then the point-source relations are expanded to include an element of perfectly diffusing luminous surface; and, finally, surface integration is employed for sources with perfectly diffusing, uniformly luminous surfaces. If the surface source is not perfectly diffusing or if it is not uniformly luminous, if a volume source is used, or if diffusing media are present, then all the equations must be examined most carefully and modifications must be made to fit the particular conditions of the problem.[24]

What is needed is a basic theory of sufficient scope to subsume all possible special cases. An attempt is made in the foregoing paragraphs to suggest an outline of such a general light-field theory. It need hardly be pointed out that little of this material is original with the writer. The principal difference between the present treatment and the light-field theory of others is that instead of employing all the older concepts and units, plus a large collection of new ones, I have tried to keep the number of concepts at an absolute minimum and to relate these concepts as closely as possible to the remainder of physics.

Evidently, the greatest advantage of the new methods is their generality. A second factor is their closer relation to the established methods of physics. Of lesser, but not negligible, importance are the improved methods of calculation. The theory of the light field gives three new methods of calculating flux density and two new methods of calculating total flux. Also, the basic method of obtaining **D** (the solid-angle method) is developed most directly under the new system.

The principal weakness of the theory in its present form appears to be that **D** is not always very closely related to anything that would ordinarily be measured. If the sources are all on one side of a specified surface, the flux density at this surface is obtained directly from **D**. But if there are luminous sources on *both* sides of a surface S, then the projection of **D** on the surface normal gives a measure of the *net* radiant flux through S, or the flux in the sense of $\mathbf{N}_1$ minus the flux directed in the opposite sense. Though interesting, this net flux density does not always give the desired information. Within a blackbody, for example, **D** is everywhere zero, which tells nothing whatever about the flux density on the walls.

The artificiality in the present treatment arises from the fact that both flux density and selance are actually scalars in a five-dimensional continuum, though they are treated here as three-dimensional quantities. It may be advisable to develop a five-dimensional light-field theory; though even if such a theory existed, the three-dimensional methods would probably be used in most cases because of their greater simplicity. The theory of the light field is still far from a complete discipline, but even today it possesses advantages over the methods of Lambert and it gives promise of developing into an important division of geometrical optics.

[24] R. Straubel, "Über einen allgemeinen Satz der geometrischen Optik," Physik. Zeits. **4**, 114 (1902). M. Labussière, "Existence géométrique d'un invariant général des faisceaux de rayons se réfractant suivant la loi de Descartes et ses applications à l'optique géométrique et au rayonnement," Comptes rendus **174**, 675 (1922). M. Herzberger, "On the Fundamental Optical Invariant," J. Opt. Soc. Am. **25**, 295 (1935). K. Schwarzschild, *Über Diffusion und Absorption in der Sonnenatmosphäre* (König. Preuss. Akad. d. Wissen., Sitzungsberichte, Berlin, 1914), p. 1183.

The Operating Characteristics of Incandescent Lamps*

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I. The Laws of Radiation Point to the Use of Tungsten for Filaments

INCANDESCENT electric lamps produce light because their filaments are heated electrically to such elevated temperatures that a part of the radiant energy they emit is visible to the eye. According to the known laws of radiation, the higher the operating temperature, the greater the energy radiated and, within the limits of known filament materials, the higher the operating temperature, the greater proportion of this radiant energy is visible to the human eye.

These fundamental laws of incandescence lead to the use of lamp filaments of high melting point. The first practical filament was carbon. Then came metal filaments of osmium, tantalum and finally tungsten.

Table I gives the melting points of several elements that have some indicated value as lamp filaments.

Carbon, while it has a very high melting point is limited as a filament because of its high vapor pressure. In fact, in vacuum and under ordinary pressures, it passes directly from the solid to the vapor.

Carbon filaments sublime rapidly at incandescence and this shortens the lamp life at high filament temperatures. For a reasonable length of life, it is necessary to hold down the operating temperature of carbon filaments. They ordinarily operate at a temperature of about 2000°K at which they will produce about four lumens of light for each watt of electricity consumed.

Besides its high melting point, tungsten radiates selectively with low percentages in the infrared, it has a very low vapor pressure, is quite stiff at incandescent temperatures and is a fairly common element in the earth's crust. In addition, the fact that tungsten has a positive resistance coefficient gives tungsten lamps great stability. Their life, light output and wattage consumption characteristics vary relatively little on varying voltage. All of these facts which favor tungsten reveal why it is still the most important light source and will be for some time to come.

Figure 1 shows the so-called "tungsten characteristic curves" with the performance characteristics correlated to varying percentages of normal voltage. This group of curves shows the practical life characteristics of the tungsten filament as well as the well-known radiation characteristics. Tungsten filament lamps ultimately "burn out" when the wire at some one spot has become reduced in diameter to such an extent that it melts. This reduction in diameter in normal lamps is the result of sublimation of tungsten. The sublimation or evaporation rate increases enormously as the operating temperature of the filament is increased. This explains the steep slope of the life curve.

II. The Laws of Economics Demand Maximum Lamp Efficiency With a Length of Life Adequate for Convenience

A lamp such as a standard 60-watt type retails for 15 cents but during its life it consumes electric current that costs, in general, at least ten times as much. For example, a 60-watt, 1000-hour lamp will consume 60,000 watt hours of electricity during its life. In the average American home today, at an average power rate of 4.5 cents per kw-hr., this current will cost $2.70 or 18 times as much as the lamp.

The efficiency of the lamp determines how much light will be obtained from the current

Table I.

	Melting Point
Carbon	3490°C
Molybdenum	2620°C
Osmium	2700°C
Tantalum	2850°C
Tungsten	3382°C

* Based on a paper under the title of "Incandescent Lamps" in the Symposium on The Optics of Illumination presented at the Niagara Falls Meeting of the Optical Society of America, October 27, 1938. Published in this journal on invitation from the editor.

consumed so that for maximum return for each lighting dollar it is far more important that the lamp be of high effectiveness than of low cost. In fact, in the average American home a 1 percent increase in the efficiency of the 60-watt lamp would be just as important to the user as an 18 percent reduction in the price of the lamp.

Increased efficiency may be obtained by operating the lamp filament at a higher temperature with a resulting shorter life or by designing and making the lamp so as to produce more light for the wattage consumed without affecting the lamp life.

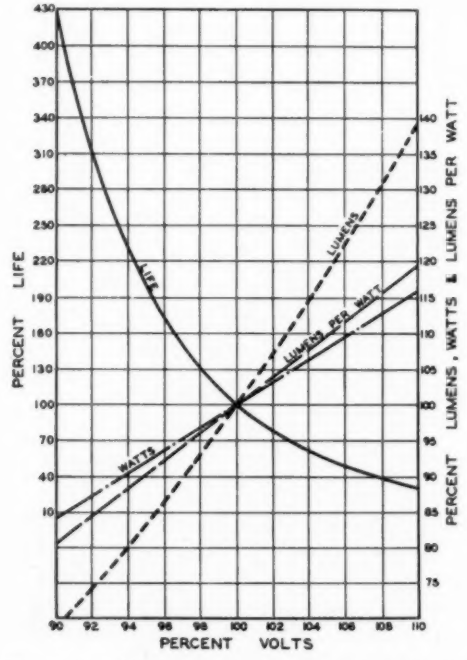

FIG. 1. Graphic representation of the effect which the terminal voltage of a tungsten filament Mazda lamp has on its life, lumen output, watt consumption and light efficiency.

The most economical life of a lamp for ordinary household use, with lamp prices and current cost today, is in the neighborhood of 300 hours. In other words, neglecting labor and inconvenience of outages and replacements light would be bought most cheaply if the present standard 60-watt Mazda lamp were designed for 300 hours life. Years of experience, however, have shown that a more practical life value for this type of lamp is 1000 hours. This is, perhaps, somewhat longer than should be but has been widely accepted as a satisfactory compromise which has proved highly successful and acceptable under widely varying conditions of use and cost.

Following the carbon lamp came improved lamp filaments of osmium, tantalum and then tungsten with the filament wire operating in vacuum. By coiling the filament, it became practical to operate the tungsten wire in an atmosphere of inert gas such as nitrogen. Less heat was drained from the filament by the filling gas of argon and still less loss was encountered when the filament coil was recoiled on itself. Step by step the light output of the lamp was increased until now the 60-watt Mazda lamp operates at 13.8 lu/w, whereas the early carbon lamps operated at only 3 to 4 lu/w.

High efficiency modern lamps depend upon controlled crystal structure within the filament wire. Although tungsten wire is relatively stiff even at incandescence, the coils of the early gas-filled lamps frequently sagged out and occasionally twisted. The sag exposed more surface of the filament wire to the cooling effect of the gas and reduced the efficiency of the lamp. Twist in some instances resulted in short-circuiting and early burn-out. Crystallographic analyses showed a relationship between the internal crystal structure of the wire and the sag and twist of the filaments and following this knowledge came the present nonsag and nontwisting wire. Today, tungsten filament wire can be so made as to control the crystal growth in the final lamp. This has been carried to such a point that not only do coiled filaments resist sag, but today it is practicable to use recoiled filaments in lamps for ordinary use. Standard 50- and 60-watt Mazda lamps are now made in this manner providing a 10 percent increased light output due to the reduced loss of watts to the filling gas. Fig. 2 shows this double coil construction.

Figures 3 and 4 show pure and treated tungsten crystal forms. Crystals are stretched out sometimes to a length of three feet in the drawing process. Drawn pure tungsten quickly changes to the straight-sided structure, shown in Fig. 3, when the filament is raised to temperatures above 2000°C. Slippage of crystals along the flat faces caused offset on alternating current and also sag.

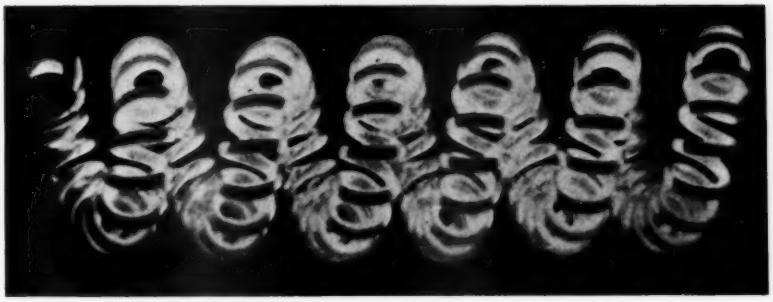

FIG. 2. This is how the high efficiency filament in a 60-watt Westinghouse Mazda lamp looks when it is magnified. Recoiling the coil on itself reduces the amount of wattage drained away by the gas in the bulb and increases the amount available for light.

Figure 4 shows the present typical nonsag structure used in most coiled filament lamps today. The natural crystal growth has been restrained by the addition of certain chemicals to the metal resulting in the structure shown. Crystals grow with their greatest length along the wire which prevents transverse slippage. Crystal grains interlock one with another giving high mechanical strength and in lamp manufacture this structure is created almost instantly to prevent sag during the period of crystal growth.

The significance of the progress made in lamp making is generally appreciated only by those who have given it some study. Disregarding the carbon, osmium and tantalum filaments, the progress with tungsten alone is truly remarkable. The chart in Fig. 5 shows the step-by-step improvements made in the 60-watt Mazda lamps from 1908 through the next thirty years of effort.

The 1908 lamp was made with a squirted tungsten filament, mounted in vacuum and had an initial lumen output of about 475 lumens. The 60-watt lamp of today is made with drawn tungsten wire which is coiled and then coiled again and which is operated in an inert atmosphere of argon gas. It has an initial lumen output of 834 lumens. As indicated on the chart, the improvement in the efficiency of this 60-watt lamp resulting in almost double the light output per watt of current consumption is the result of many factors. Invention and discovery of new materials was naturally a primary factor but precision of manufacture, in other words, care and skill in the factory itself, contributed more than the creation of new designs or the discovery of new materials.

The importance of this achievement can perhaps best be revealed by comparing the cost of the illumination we have in this country today with present lamps, with the cost of that same amount of light were we limited to the lamp of 1908. Last year in this country 500 million lamps were purchased. These lamps had an average wattage of about 60-watts. Approximately thirty billion kilowatt hours of electricity were consumed at a cost of almost one billion dollars. Had we been forced to obtain this amount of light with the lamp of 1908, we would have used 880

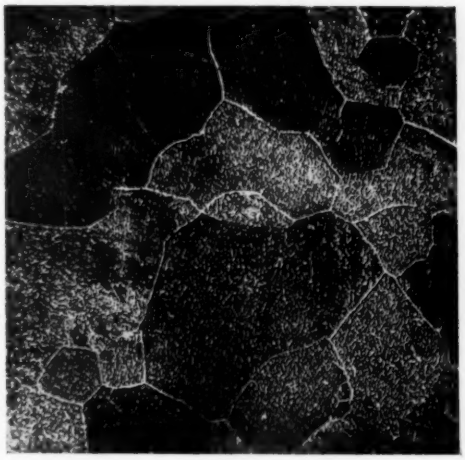

FIG. 3. Crystal forms assumed by pure drawn tungsten when its temperature is raised to 2000°C.

million lamps, we would have consumed 53 billion kilowatt hours of electricity. We would have spent for the extra current alone a sum of almost three-quarters of a billion dollars in 1938 alone.

This shows the significance of thirty years of effort. Consider the improvements during only the last twenty years since the World War. The rise in efficiency has been over 40 percent. The American public received during this period over 8 billion dollars worth of extra light as a result of these years of better lamp making. When the Mazda lamp manufacturers finish their present program on the recoiled high efficiency filaments, the public will receive added light worth to them about 40 million dollars each year.

III. Light Distribution from Incandescent Lamps is Now Fully Controlled

The filament of a lamp may be arranged within the bulb in any one of many ways. This arrangement, generally called filament construction, determines the exact distribution of light from the lamp. In general, however, this arrangement can only provide a symmetrical distribution of light. Fig. 6 illustrates the distribution pattern obtained with two common types of filament construction.

Bulb finishes, in general, diffuse the light and are primarily provided to reduce glare. The white bowl finish, however, became a partial reflector and now the silvered bowl finish becomes a complete reflector.

Bulb shapes had little effect on the distribution of light until the finishes became highly reflecting. Now the walls of the bulb are formed in the shape of a reflector and are provided with a reflecting finish so as to result in almost complete control of the distribution of light from the filament as shown in Fig. 7.

IV. Practical Fixture Design Considerations

Most incandescent lamps are operated in fixtures of one kind or another. It is very important for all concerned that these fixtures and the lamps operate well together. Today the situation is excellent, and everything possible should be done to maintain it that way.

New types of lamps require new fixture design principles, and always a new generation of designers enter the field to keep it alive. For these reasons, it is worth while to restate the general requirements for good fixture design.

First, it is very important that adequate clearance be allowed around each lamp. Each individual lamp varies somewhat from every other in its dimensions. While these variations are reduced

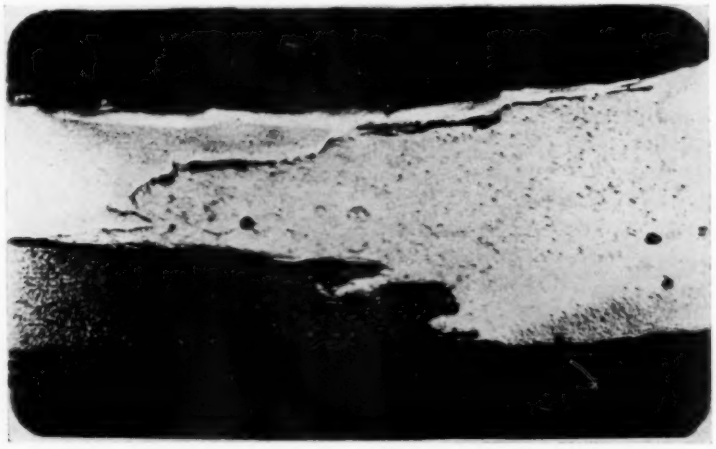

Fig. 4. Crystal forms that develop in a filament wire made of treated tungsten. These crystals are elongated and interlocked and represent the best form for ordinary house lighting lamps. Tungsten wire so treated acquires the important "nonsag" property and also has great strength.

from year to year, it is nevertheless important that fixtures leave as much clearance as possible. A good working rule is to provide $\frac{1}{4}$" minimum clearance at all points around the bulb. Shoulder clearance at the base should meet the requirements of the standard shoulder gauge.

The lamp manufacturers provide drawings of their product to assist in design work. Fixture designers should use those drawings rather than individual lamps for their fundamental design work. This eliminates the danger that the lamp selected may not be representative of the average product.

It is important that operating temperatures of the fixture be held within bounds. Sockets with paper lining should be held to 125°C or lower. Porcelain sockets may operate hotter but should never exceed 175°C or the lamp basing cement may be destroyed.

The temperature of the lamp bulb may, in general, run quite high without injury to the lamp performace. For soft glass bulbs, the so-called "hot spot" temperature should not exceed 375°C and for hard glass bulbs 425°C. These temperatures when measured with a thermocouple and a new unblackened lamp will ordinarily be safe throughout the entire life of the lamp.

Ventilation of fixtures in order to reduce lamp temperatures is ordinarily to be avoided. This is apt to introduce dust and dirt which reduces the efficiency of the fixture. Furthermore, ventilation unless carefully carried out may actually cause a rise in temperatures particularly of the lamp base and socket due to hot air rising along the bulb.

No part of the lamp fixture should be hung on the lamp bulb. There is no question but that this rule is frequently broken and without serious results. On the other hand, in other cases appreciable pressure has been placed upon the lamp bulb which has caused serious trouble. This is particularly true with larger sized lamps in which the relative thickness of the bulb wall is less and the heat is greater. In some instances pressure combined with a steep temperature gradient has caused the bulb to crack and occasionally give way.

Naturally the lamp should operate at normal voltage held to a minimum of momentary variation. Adequate wire size of the fixture and adequate current capacity in the sockets are just as important as adequate wire size in the lighting circuit.

V. New Types of Incandescent Lamps

Analyzing the progress of the last few years in filament lamp making, it is found that new light sources are brighter and more efficient. Light distribution is under more accurate control and

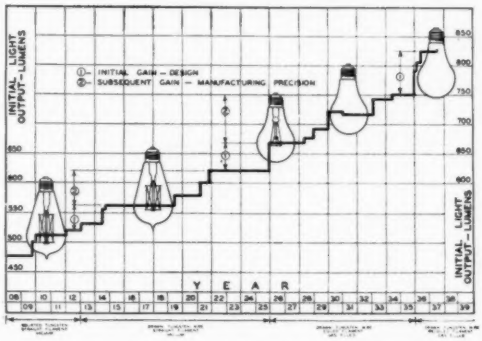

Fig. 5. Graphic illustration of improvements in the 60-watt Mazda lamp during 30 years, resulting from research and engineering development and improved manufacturing technique.

lamps with more widely varied distribution of their radiant energy are available. Lamps are smaller in size but higher in power. New shapes are available, lamp dimensions may be obtained within narrower limits and new flexibility is offered with multi-filament lamps. There is a wider choice offered in color with new pastel shades for decorative lighting. These and other characteristics when considered altogether reveal a really great deal of progress in incandescent lamp making. Perhaps the best presentation of the recent improvements made in filament type lamps would be to take each characteristic by itself and illustrate it with one or more of the newer types of lamps.

Brighter filaments

The 1000-watt and 1200-watt, T-12 bulb, biplane filament projection lamps designed for 10 hours average life are the brightest picture projection filaments now available.

More efficient lamps

The recoiled filaments are now standard in 50- and 60-watt Mazda lamps. This high efficiency

filament construction increases the light output about 10 percent.

General lighting lamps within recent years have been made in such a way that almost pure argon can be used without danger of arcs within the lamp. A majority of the gas-filled Mazda lamps now made contain almost no nitrogen dilution in the filling gas.

Blackening control has progressed, raising the mean efficiency of lamps throughout their lives. The tungsten collector plate in projector lamps and the mesh wire screen in medium bipost lamps are the most recent and interesting devices used for this purpose.

New control of light distribution

Bowl silvered lamps, introduced some years ago, redirect the downward hemisphere of light and find wide use in indirect lighting. Now the bulb walls of the projector and reflector lamps are formed in special shapes and provided with mirrored surfaces so as to redirect the upper hemisphere of light downward for direct lighting.

Detailed studies within the lamp itself reveal ways to smooth out the distribution of light or otherwise control it. The C-6 filament photo-cell exciter lamp, created over ten years ago, is now improved upon by the use of an arched form of coil providing almost uniform intensity in the horizontal plane.

Greater power

While the 10-kilowatt standard lamp for airport floodlighting service is still the largest commercial size of lamp, 50-kilowatt lamps are available for special uses. The 1000-watt photoflood provides 33,500 lumens from a lamp the size of the standard 300 watt. The No. 75 photoflash, at its peak, provides an intensity equal to that of twenty 10-kilowatt lamps.

Lamps are smaller

The use of the coiled-coil filament in the 50- and 60-watt standard lamps reduces the drain of heat from the filament by the filling gas. This, in turn, reduces the operating temperature of the lamp and, as a result, it is possible to make both of these lamps in the A-19 bulb instead of the A-21 bulb, thus enlarging the sphere of usefulness of these two sizes.

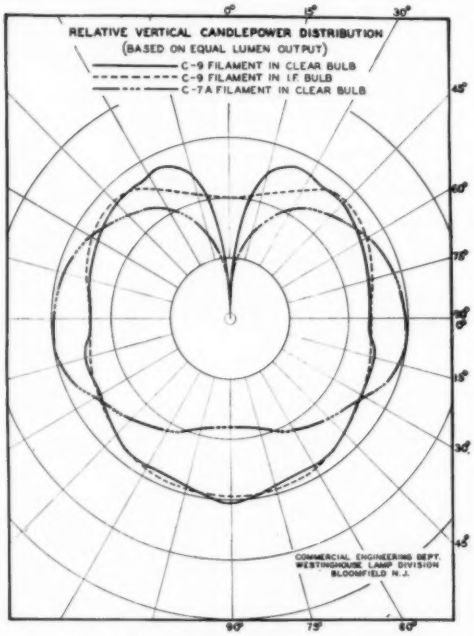
RELATIVE VERTICAL CANDLEPOWER DISTRIBUTION
(BASED ON EQUAL LUMEN OUTPUT)
C-9 FILAMENT IN CLEAR BULB
C-9 FILAMENT IN I.F. BULB
C-7A FILAMENT IN CLEAR BULB
COMMERCIAL ENGINEERING DEPT.
WESTINGHOUSE LAMP DIVISION
BLOOMFIELD N.J.

FIG. 6. Distribution curves obtained with two common types of filament construction such as used in Mazda lamps for general lighting service.

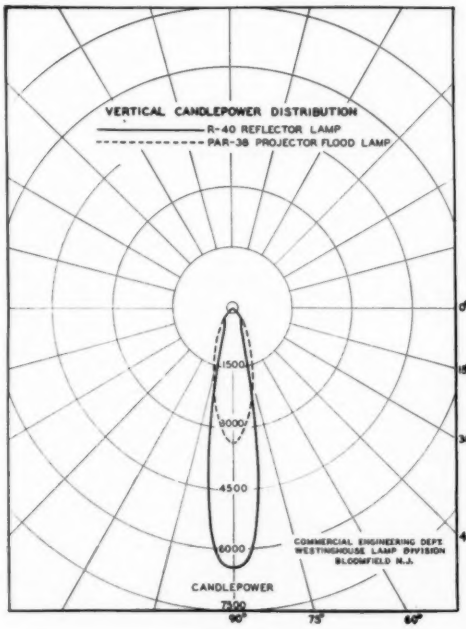

FIG. 7. Distribution curves of the 150-watt projector flood lamp and the reflector lamp.

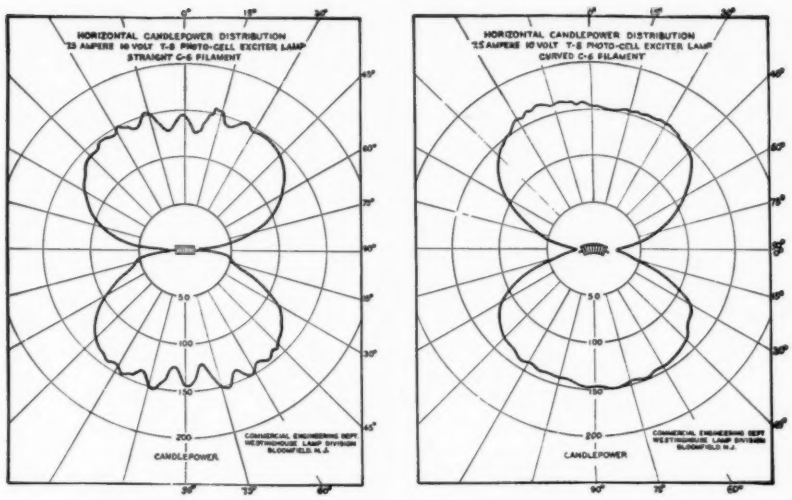

FIG. 8. Distribution of light from a straight helix and from a curved helix of tungsten filament, such as used in photo-cell exciter lamps for sound motion pictures. The smoother distribution of light improves quality of sound reproduction.

The medium bipost structure in the 500-watt, 750-watt and 1000-watt multiple types and in the 4000- and 6000-lumen series types of lamps cuts the lamp dimensions down to about one-third of their former size.

New shapes

The tubular lumiline lamp, introduced only four years ago, answered a great need for "streamlined shapes." About a million of these lamps are now sold each year in the United States.

More accurate dimensions

The medium bipost general lighting lamps are held within dimensional tolerances entirely impractical for the older types of lamps. These make possible new closer fitting fixtures with more precise light control.

The PR-2 and PR-3 prefocus flashlight lamps provide precision filament location in flashlights similar to that already provided in automotive headlight lamps.

More flexibility

Double filament lamps are now available for many types of service requiring flexibility in the individual lamp. Most widely used of these are, of course, the double filament automobile headlight and the so-called three-light lamps used in indirect portable lighting fixtures.

New colors

The lumiline lamp introduced pastel shades to blend with interior decoration.

Greater strength

Each year, lamps are more resistant to vibration and shock. Today, ordinary lamps survive treatment which ten years ago would have been disastrous. New types of lamps, however, such as the vibration and rough service lamps, are available to meet the extreme requirements of service where needed.

Cheaper

In 1907, the 60-watt lamp was introduced at a list price of $1.75. This lamp now lists at 15 cents. In 1933 the 100-watt, T-8 projection lamp was announced at a list price of $2.00. Today, this lamp lists at only 85 cents.

This has been a brief report of real progress—better lamps for less money, raising the standards of lighting in our country. The surface is scratched but much remains to be done. Filament lamps will still be improved year by year as newer types of sources are introduced and perfected to fill the need for better light.

High Efficiency Mercury and Sodium Vapor Lamps*

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(Received January 19, 1939)

WHEN Peter Cooper Hewitt introduced the d.c. mercury lamp thirty-five years ago, its efficiency was two or three times that of contemporary incandescent lamps. Intensive development of the latter equalized the difference during the following twenty-five years until radical changes in electric discharge lamp design and operation reestablished the above ratio.

The physics of light production in electric discharge lamps, as understood at present, has recently been ably and extensively discussed[1] and is foreign to this paper which is limited by the symposium subject to external electrical and optical characteristics of significance in illumination.

The early mercury arc was inherently a d.c. device whose negative or cathode electrode was a mercury pool placing serious limitations on the position of the lamp and the method of starting the electric discharge.[2] Alternating current operation was only possible by resorting to a rectifying circuit which provided a pulsating d.c. discharge through the lamp tube.[2] Ballasting was required to stabilize the arc and this series impedance entailed a certain loss of energy varying from 35 percent for the d.c. arc to 41 percent for the resistively ballasted rectifying type a.c. arc, and 27 percent for a similar reactively ballasted lamp. Electrical limitations in the rectifying circuit and thermal limitations in the glass tube made this lamp inherently a low temperature, low pressure device giving an efficiency of about 25 lumens per watt in the arc. This impressive efficiency was seriously reduced by the arc ballasting to from 15 to 19 lumens per watt over-all, depending upon the kind of ballasting used.[3]

An arc operated at a temperature of about 350°C and a vapor pressure of one atmosphere in a fused quartz arc tube had early demonstrated that the efficiency in the arc could be increased to forty lumens per watt if an inexpensive glass could be found to operate at this temperature. It was recognized that an alternative and additional means of increasing the efficiency of the a.c. mercury arc would be by operation directly from the supply using low loss reactive ballasting instead of a rectifier circuit and resistive ballasting.

So-called "hard glasses," similar to the Pyrex of the laboratory and the kitchen, permit the higher energy input per unit of mercury vapor necessary for increased efficiency. Activated solid electrodes permit arc starting and operation on relatively low a.c. voltages with a reactive ballasting loss as low as 10 percent. While these two developments adequately account for the new high efficiency mercury lamps, there are certain additional features of possible interest.

An advantage inherent in metal vapor arcs is that very high vapor pressures, high energy per unit volume of vapor, can be obtained by virtue of the rapid increase of vapor pressure with temperature, in contrast with the only linear change of gas pressure with the absolute temperature. Even if it were desirable to do so, it would be difficult to make an electric discharge gas lamp, neon for example, with an initial pressure in excess of one atmosphere without resorting to the greater difficulty of liquefaction. From an initial pressure of one atmosphere a final pressure of perhaps four atmospheres could be attained in a fused quartz neon arc, but at such a temperature the vapor pressure of liquid mercury would be about two hundred and fifty atmospheres. While this is of unique value in securing the efficiency of high pressure operation at practical temperatures in the case of the mercury arc, it also obviously makes for thermal and electrical instability as the arc voltage goes up almost linearly with pressure. The use of activated elec-

* Presented by invitation in the Symposium on The Optics of Illumination at the Niagara Falls Meeting of the Optical Society of America, October 27, 1938. Published in this journal on invitation from the editor.

[1] S. Dushman, J. Opt. Soc. Am. **27**, 1–24 (1937). See Bibliography of this reference.

[2] L. J. Buttolph, Rev. Sci. Inst. **1**, 487 (1930); *ibid.* **4**, 206 (1933).

[3] R. C. Kelting and L. J. Buttolph, Trans. I.E.S. **33**, 643 (1938).

trodes and compact electrode chambers made it at once possible to use a measured quantity of mercury so adjusted to the volume of the arc tube as to insure any desired pressure and arc voltage upon the complete vaporization of the mercury. This complete vaporization of the mercury is the practice in all of the present commercial types of high intensity mercury lamps except the 1000-watt, 75-atmosphere water-cooled arc.[4] Upon starting these lamps, the arc voltage rises rapidly to this predetermined value and therafter remains practically constant regardless of changes in supply voltage, arc current or external temperature. These arcs are, however, generally inclosed in an integral jacket or bulb to secure a rapid initial heating and to insure that there is no condensation of mercury under condition of low supply or exceptional cooling of the lamp tube or bulb.

Since these high intensity mercury arcs operate at pressures of one atmosphere or more, the discharge is constricted in the arc tube. In all cases, this results in a variation of brightness across the arc and in some cases, it limits the operating position to the vertical as convection currents in the vapor force the hot central core of the arc against the upper side of the arc tube to destroy it in the case of a glass tube.

These vapor pressures also determine other characteristics in the operation of these lamps. Thus several minutes from starting are required for the arc tube to attain the pressure necessary for full light output and upon extinction of the normally operating arc a similar interval is required for it to cool, restart and regain its normal temperature.

Two types of these arcs have resulted from the use of hard glass arc tubes and fused quartz arc tubes. Typical of the former is a 250-watt, H2 lamp, a 400-watt H1 lamp, and an 800–1000-watt lamp in development.[5] The H1 and H2 are shown in Fig. 1. These lamps operate at a pressure of substantially one atmosphere. Typical of the lamps with fused quartz arc tubes are the 85-watt, H3, the 100-watt H4, and the 250-watt H5 shown in Fig. 2. These arcs operate at pressures from 30 to 15 atmospheres and in any position

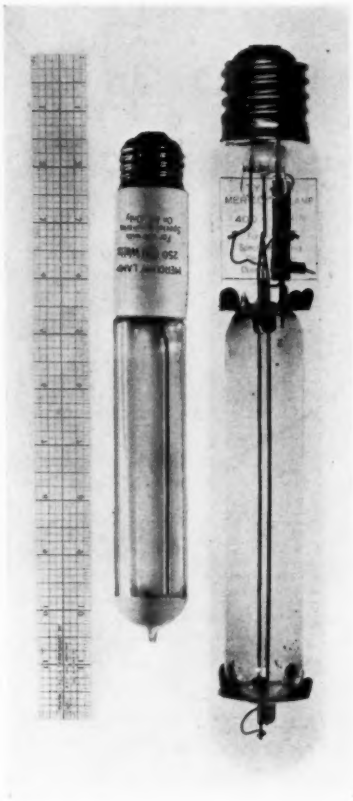

FIG. 1. H1, 400-watt; and H2, 250-watt, high intensity mercury arcs.

insofar as a slight deflection of the arc is not objectionable.

In Table I the characteristics of these lamps are compared in terms of the commonly used auxiliary equipment. For practical purposes the maximum beam candlepower of these line sources is one-tenth their total lumen output. Because of the nonsinusoidal arc currents and voltages, these arcs of themselves all have an apparent power factor of from 0.85 to 0.90 as may be calculated from the data given. When operated in series with reactive ballast, there is a superposed true power factor of about 0.65 which is generally corrected in industrial devices by the use of a multiple capacitor and so is not apparent in the tabulated data.

The H1 and H2 lamps are used almost exclusively for industrial and highway lighting,

[4] E. B. Noel and R. E. Farnham, J. Soc. Mot. Pict. Eng. **31**, 221 (1938).
[5] J. A. St. Louis, Trans. I.E.S. **31**, 583 (1936).

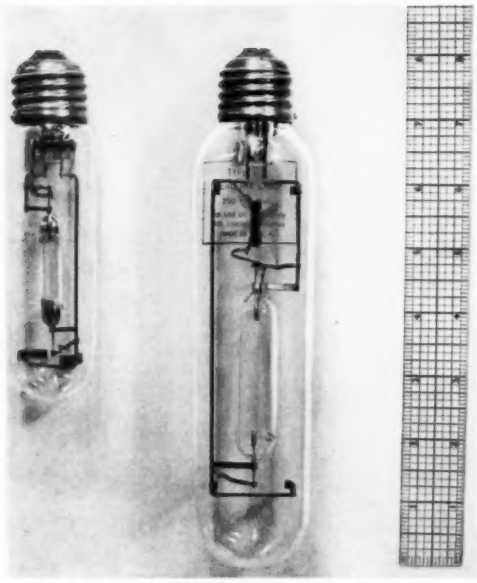

FIG. 2. H4, 100-watt; and H5, 250-watt, capillary type high pressure mercury arcs.

either alone or combined with incandescents. They are usually mounted base-up in conventional type reflectors and diffusers.

The H3 lamp, having the highest brightness of the air-cooled lamps, can be used in many places as alternative to a 250-watt incandescent projection lamp where the mercury spectrum is of advantage, as for microscope illumination, sound track printing and narrow beam spotlighting.

The H4 lamp is similar in its applications and is preferred for its lower voltage where a lower brightness is satisfactory.

The H5 lamp is a possible alternative to the H2 for illumination and more useful with reflectors because of its much smaller source size.

The color of all mercury arcs is so largely subjective that any attempt to compare it with daylight is very difficult and always deceptive from an illumination standpoint. Since both color and efficiency is a matter of relative energy distribution and eye sensitivity an attempt is made in Fig. 3 to compare an incandescent lamp, a sodium lamp, a Cooper Hewitt lamp and a high intensity mercury lamp by assigning an arbitrary width to the spectrum lines so that their areas are proportional to their relative intensities and the total line areas represent the visible energy necessary to produce equal luminosities by these sources as represented by the ruled portions of the line areas. The effect of energy distribution on color and efficiency is obvious. It should be remembered that the over-all luminous efficiency of any source is also conditioned on the efficiency with which the electrical energy is converted into radiant energy in the visible range, regardless of the distribution in this range.

In recent years the color of the light from mercury lamps has been frequently compared with daylight and incandescent lamp color by describing its subjective color in I.C.I. tri-

TABLE I. *Based on data from B. T. Barnes, General Electric Company, Cleveland, and L. B. Johnson, General Electric Vapor Lamp Company, Hoboken, N. J. C. H., Cooper Hewitt.* Na9, *sodium lamp.*

		C.H.	H1	H2	H3	H4	H5	H6	Na9
	Arc watts	270	400	250	85	100	250	1000	200
	Arc volts	74	143	70	250	130	135	840	30
	Arc amperes	3.65	3	3.9	0.4	0.86	2.06	1.4	6.6
	Source length	127 cm	15.25	10	1.8	2.4*	4.3*	2.5 cm*	23 cm
	Source diameter	2.5 cm	3.5	2.85	0.4	0.75	1.3	0.2 cm	7.6
	Max. candles per sq. cm	2.1	50	50	900	400	300	30,000	6
	Lumens	6800	16,000	7500	3000	3500	10,000	65,000	10,000
	Lumens per arc watt	25	40	30	35	35	40	65	50
	Atmospheres pressure	.0003	1.0	0.5	30	8	0.4	75	10^{-6}
A	5770–91	26.3	127	55	19.2	30.5	104	300	
	5461	81	131	57.5	33.5	33.6	90.5	510	
	4916		3	1.5		1.6	4.3		Microwatts
	4358	82	92	44.5	27.1	26.9	72	510	per sq. cm
	4047	59	44.5	23.6	14.5	14.2	38.2	270	at 1 meter
	3650–63	30	41	22.5	25.7	24.5	70	240	

* See reference 4 for data on continuous part of spectrum.

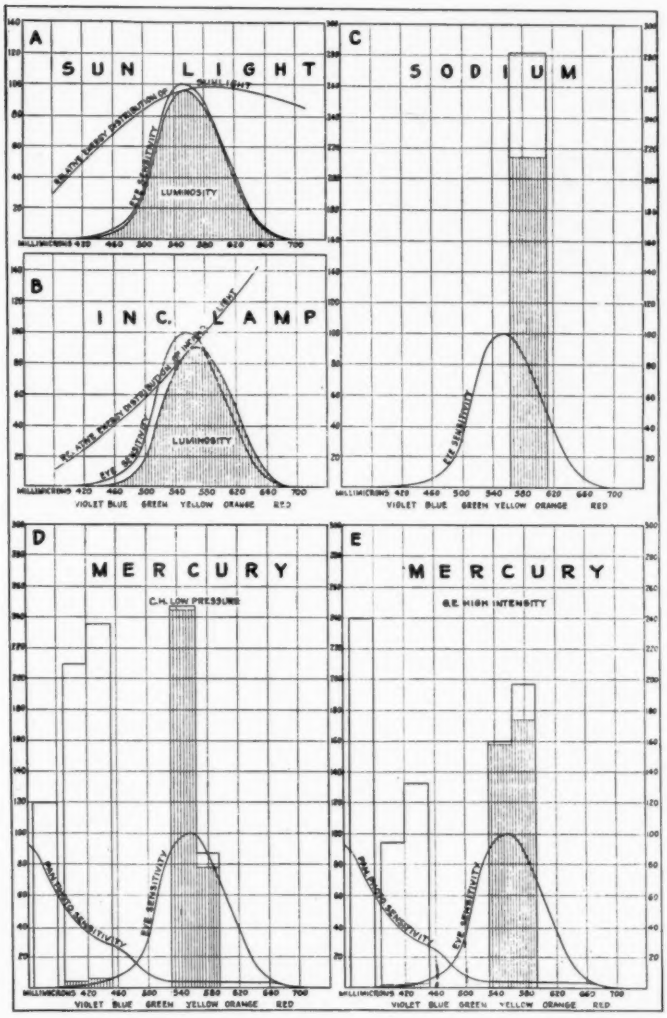

FIG. 3. Graphic indication of the energy required to produce comparable luminosities by light of various energy distributions.

chromatic sensations, usually without warning to the layman that this is no adequate criterion of the light from the standpoint of illumination practice where the appearance of colored objects is important. These higher pressure mercury lamps provide slightly more justification for this treatment, in that a continuous background begins to appear in their spectrum and increases with pressure to about one-third the relative red intensity of sunlight for the water-cooled capillary lamp. This brings the subjective color due to the line spectrum to a close match to daylight.

As the high brightness of all these lamps, from the H3 to the H6, inclusive, makes them useful for many scientific uses, it should be noted here that this advantage for many applications is offset by the broadening of the spectral lines so that the H1, one atmosphere, lamp may be the more useful in spite of its lower brightness.[4] Another characteristic of these lamps of significance for the laboratory user is that the inner bulb or arc tube proper of the H1 and H2 lamps,

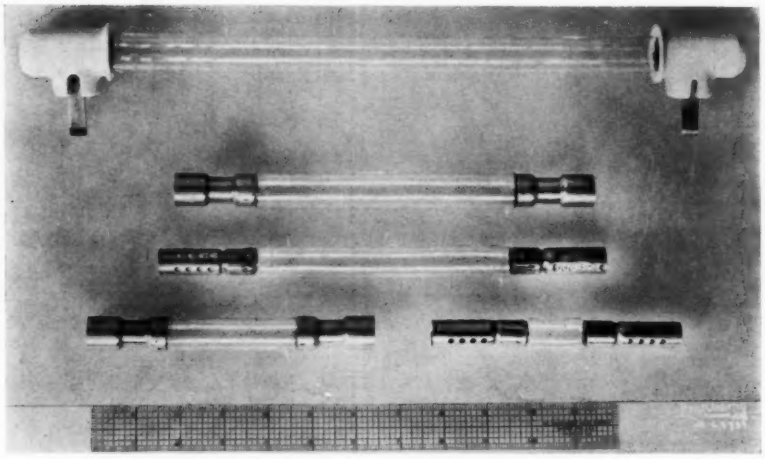

FIG. 4. Five different sizes of the alternating-current fused-quartz arc lamps, showing relative sizes, constructional details of terminals and code numbers.

and in some cases the outer bulbs of the H3, 4 and 5, lamps develop a marked absorption for the 3660A line at their normal operating temperature. This means that the H1 and 2 are not efficient for the production of fluorescence by 3660.

The H3, 4 and 5 lamps, whose compactness permits efficient use with reflectors and projectors, are of outstanding efficiency in the production of 3660A radiation when provided with outer bulbs which are permeable to the 3660 radiation, and such lamps are thus very useful for the activation of such fluorescent materials as are used in theatrical, decorative, and sign lighting. They are similarly useful in many photoprinting applications dependent upon a high intensity of near ultraviolet. The H3 lamp is, for example, being used in the ultraviolet printing of the sound track on film.

While the shift in relative energy distribution in the direction of increased visibility with increased operating pressure had an important bearing on efficiency, an equal gain has been made through a minimization in ballasting losses. Activated electrodes permit a.c. operation and the use of reactive ballasting with an iron and copper loss as low as 10 percent of the total. The resulting power factor is corrected by compact low loss condensers. Self-starting of the discharge is secured by an initial glow discharge in low pressure argon to an auxiliary electrode. This type of a.c. operation imparts a cyclic variation to the light output which persistence of vision masks at 120 cycles, but which does give stroboscopic effects with moving objects. This has not been found objectionable in industrial lighting and can be minimized by operating adjacent lamps on a phase-splitting auxiliary or on a three phase supply.

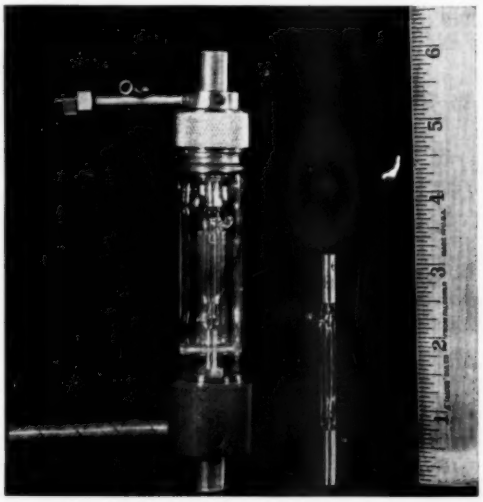

FIG. 5. H6, 1000-watt, capillary type water-cooled high pressure arc with casing.

These new mercury arcs are so compact that they can be used in standard reflectors and diffusers designed for incandescent lamps of about double the wattage rating with distribution characteristics such as to make their utilization in industrial lighting entirely in accord with established incandescent practice and of little interest for this paper.

Although they are not of use for illumination, there is a related line of new quartz mercury arcs that should be mentioned here.[6] They are of the simple construction shown in Fig. 4, use the same type of electrodes as the H series of lamps, and have electrical characteristics determined by the use of a limited quantity of mercury. They range in size from 150 to 1200 watts as shown in Fig. 5, and have been made up to a length of about four feet and a rating of 3500 watts. Although these arcs have an efficiency of 30–35 lumens per watt, they are intended primarily as sources of ultraviolet for the sterilization of water, the irradiation of food materials, photo reproduction and a great variety of photochemical processes.

Another high efficiency, high pressure lamp only indirectly used in illumination is the H6

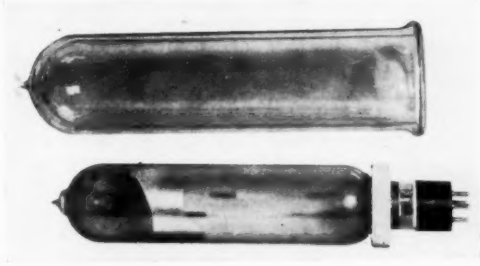

FIG. 6. Na9, 200-watt, 10,000 lumen sodium arc and its insulating casing.

water-cooled, 1000-watt quartz capillary arc[4] Fig. 5. This energy dissipated from a light source 2 mm in diameter by 25 mm long gives an initial output of 65,000 lumens. This lamp, referred to hereinbefore, operates with the mercury only partially vaporized, at a pressure of about 75 atmospheres, and with an arc voltage of about 850. The brightness is about 30,000 candles per

[6] L. B. Johnson and S. B. Webster, Rev. Sci. Inst. **9**, 323 (1938).

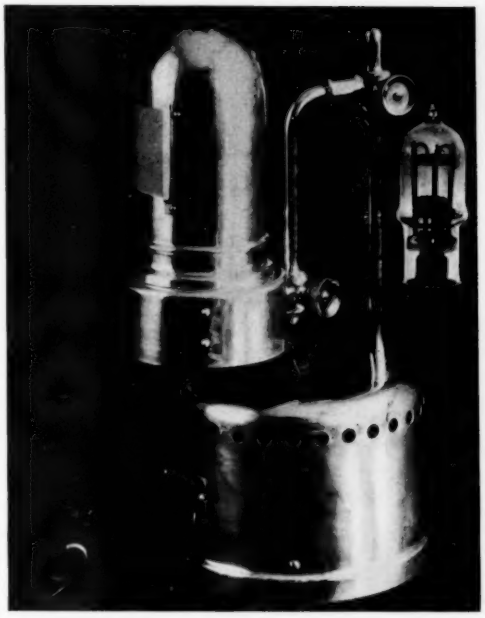

FIG. 7. Sodium Labarc, 35-watt, lamp bulb, metal casing and auxiliary support.

sq. cm or some ten times that of a comparable ribbon filament incandescent lamp. So high an energy density is possible only through the use of water forced so rapidly over the surface of the arc tube as to prevent the formation of steam and local heating.

In this lamp the spectral lines are greatly broadened and a continuous spectrum is superposed to an extent about one-third that of sunlight.[4] The high brightness and water-cooling of the lamp makes it ideal for many special photographic lighting, printing and projection problems where temperature has been a problem in the past.

The high efficiency sodium lamp as developed for use in the United States, stands in marked contrast with the newer mercury lamps, Fig. 6, in that the efficiency of the sodium lamp varies somewhat inversely with its temperature and the sodium vapor pressure.[7] It is inherently a relatively large, low intensity light source starting as a neon arc and operating finally in a saturated sodium vapor of a pressure corresponding to about 200°C, one-hundred-thousandths the pres-

[7] C. G. Found, Gen. Elec. Rev. **37**, 269 (1934).

sure of mercury at the same temperature. Even at this relatively low temperature sodium attacks all ordinary glasses, and hence a thin coating of a special vitreous material, resistant to sodium is used to protect the glass container. Since the efficiency of this lamp is dependent upon maintaining an optimum vapor pressure for a given size of lamp bulb with a minimum of heat loss, and since the efficiency varies rapidly with changes in temperature, the sodium lamp is always operated in a two- or three-wall glass insulating enclosure as shown in Fig. 6. The size of the lamp bulb makes the use of the integral insulating bulb characteristics of the H1 mercury lamp impractical.

As highway lighting on established 6.6-ampere series circuits was chosen for initial trials, the only lamp generally available for illumination is a 10,000-lumen, 200-watt lamp operating at about 30 volts in the arc. Auxiliary heating of the electrodes requires a few seconds delay in arc starting, usually provided by a thermal control switch. The area of the source is such that reflectors and refractors are of limited use.

For laboratory use there is available a small sodium lamp, Fig. 7, rated at 35 watts in the arc and 65 watts over-all. Because of the nature of the use, efficiency of operation was sacrificed to secure multiple operation with compact resistance ballasting. Like the larger sodium lamp, this operates at very low vapor pressure and the disadvantage for some applications, of low brightness, is offset by freedom from pressure broadening of the lines.

The Basis for High Efficiency in Fluorescent Lamps*

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General Electric Company, Nela Park, Cleveland, Ohio
(Received January 17, 1939)

UNTIL the last three or four years books[1, 2] and articles on luminescence rarely dealt with the possibility of using phosphors** as light sources for general illumination because only very low brightnesses were attained. Nichols, who specialized in this field, wrote in 1921 that "unless someone discovers a means of making luminescent bodies that are vastly brighter than the best now known, luminescence may be excluded altogether as a factor in artificial lighting."[3] Publications on phosphors in recent years have related principally to their use on screens for x-ray and cathode-ray tubes.

Early trials of a powdered phosphor coating on the inside wall of a low pressure mercury-discharge tube gave promising results as an experimental light source. For example, one of our first lamps, using willemite ore from Franklin, New Jersey, as the phosphor, yielded a luminous efficiency of 30 lumens per watt input contrasted with nine lumens per watt for a regular, incandescent-filament lamp of the same wattage. However, the color of the light from the fluorescent lamp was green. Extensive development work resulted in the recent commercial introduction of a line of low wattage fluorescent lamps, with luminous efficiencies of 30–35 lumens per watt for the daylight type, 60–70 lumens per watt for the green, and 3–30 lumens per watt for other colors. These efficiencies are from three to two hundred times as great as those of incandescent filament lamps of corresponding colors and wattages.

General descriptions of the lamps and their luminous and electrical characteristics have already been published,[4, 5] and are repeated only in part here. Experimental work has been carried out on tubes one to one and one-half inches in diameter, and twelve to forty-eight inches in length. The electrodes consist of coiled coils of tungsten wire coated with barium and strontium oxides; each serves alternately as cathode and anode because the lamps usually are operated, through suitable ballasting equipment, from 60-cycle a.c. supply lines. Each electrode is heated as a filament at starting, but is heated by arc bombardment during operation of the lamp. The phosphor, in finely powdered form, is applied to the inner bulb wall with a suitable binder. After sealing and evacuation, the lamps are filled with argon to a pressure of a few millimeters Hg, and a few milligrams of mercury are added.

High luminous efficiency cannot be obtained in a fluorescent lamp unless the conversion of input energy into the 2537A resonance line is relatively efficient. Table I shows that this is the case, particularly at low current densities. The spectral distribution measurements extended only to 2200A on the short wave-length side. Lines in the farther ultraviolet, particularly the 1850A resonance line, may have considerable intensity and effect in exciting fluorescence. The table shows that increasing current density increases the efficiency of conversion to all lines except 2537A. The value of the vapor pressure also affects the efficiency of production of 2537A. Fig. 1 gives curves for relative luminous efficiency; in the type of fluorescent lamp described, this is an approximate indication of the intensity of 2537A. For a fixed vapor pressure, the efficiency of production of 2537A increases as current decreases.

The temperature of the coolest part of a tube one inch in diameter, operating in still air at 20°–25°C, falls within the optimum range when

* Based on a paper under the title of "Luminescent Lamps" in the Symposium on The Optics of Illumination presented at the Niagara Falls Meeting of the Optical Society of America, October 27, 1938. Published in this journal on invitation from the editor.

[1] P. Pringsheim, *Fluorescenz und Phosphorescenz*, third edition (J. Springer, 1928).

[2] E. L. Nichols and E. Merritt, *Studies in Luminescence* (Carnegie Institution of Washington, 1912).

** This term is used here to designate both fluorescent and phosphorescent materials.

[3] E. L. Nichols, Trans. I. E. S. **16**, 332 (1921).

[4] G. E. Inman and R. N. Thayer, Elec. Eng. **57**, 245 (1938).

[5] G. E. Inman, "Characteristics of Fluorescent Lamps," Trans. I. E. S. **34**, 65 (1939).

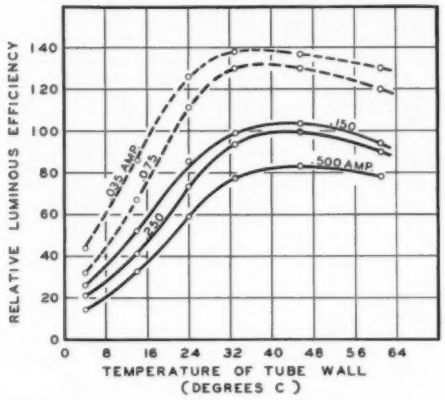

FIG. 1. Relative luminous efficiency *vs.* tube wall temperature, for various arc currents. Average for two $ZnSiO_3$ coated tubes immersed in a water bath. Diameter 1″, arc gap 16″. Cathodes heated as filaments for 0.035 and 0.075 ampere runs.

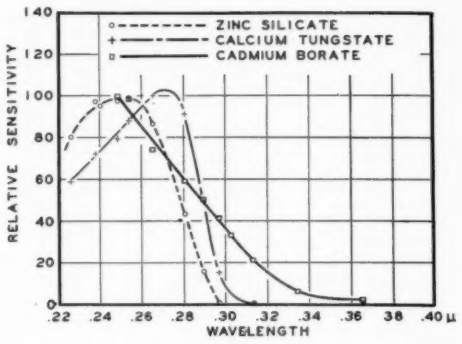

FIG. 2. Relative spectral excitation sensitivity of various phosphors.

the current is 0.25–0.35 ampere. Currents of this magnitude also give a satisfactory compromise, on tubes coated with a phosphor, between the higher luminous efficiencies obtained with lower currents and the higher total lumen output obtained with higher currents.

The high luminous efficiencies of fluorescent lamps have been achieved only with the development of synthetic phosphors whose excitation sensitivities are maximum for radiant energy of wave-lengths in the vicinity of 2537A (Fig. 2). Sulfide phosphors, whose properties have been reported in great detail in the literature, are unsuitable because they have their maximum sensitivity in the region 3600–4000A, and only about one-fourth of maximum at 2537A. Suitable phosphors have been found among the tungstates, silicates, and borates (Table II). The chemical composition of the phosphors is indicated only approximately by the formulas listed, because the proportions of constituents giving maximum luminous efficiencies are not necessarily equimolecular. Moreover, manganese usually is present as an activator.*

Since spectral distributions of the visible radiation from phosphors or phosphor mixes used in commercial lamps have been published,[5] only one example is shown here (Fig. 3). Table II indicates the distributions for several phosphors. In coated tubes, the visible radiation from the mercury discharge is transmitted by the phosphor with an intensity, perpendicular to the arc axis, which indicates less than 10 percent absorption. Consequently, the resultant spectrum combines the band spectrum of the phosphor and the line spectrum of the discharge. In Fig. 3, these lines have been represented as bands 200A wide, but their effective width in practical use is primarily dependent on the spectral reflectance characteristics of surfaces viewed under the lamps. In the case of the daylight lamp, a comparison of the spectral distribution curve for the lamp with that for actual daylight does not indicate the success of the match in practical use. Bouma's

* Some of these phosphors are covered by patents and patent applications, as are also certain processes for obtaining special color and efficiency characteristics.

TABLE I. *Efficiency of production of mercury line radiation.*

Current (Amp.)	Bulb Wall Temp.	Percent* Converted Into Each Line							Sum	Proportion in 2537A Line	Lumens per Watt*
		λ2537	3129	3654	4047	4358	5461	5780A			
0.25	48°C	62	0.53	0.45	0.59	1.30	0.86	0.18	65.9	94%	5.5
.50	57°	55	.68	.62	.86	1.45	1.26	.27	60.1	92%	7.3
1.00	69°	40	.89	.82	1.02	1.79	1.49	.39	46.4	86%	10.0

* Of positive column input, for a low pressure discharge tube of 1″ diameter in still air at 25°C.

TABLE II. *Spectral distribution of the visible radiant energy from various phosphors excited by the mercury resonance line, 2537A.*

PHOSPHOR	GENERAL COLOR	WAVE-LENGTH, IN A, FOR MAXIMUM ENERGY	SPECTRAL ENERGY RELATIVE TO MAXIMUM				
			λ4500	5000	5500	6000	6500A
$CaWO_4$	Blue	4400	98	60	24	8	2
$MgWO_4$	Blue-white	4800	86	97	56	26	9
$ZnSiO_3$	Green	5250	1	33	48	4	0
(Zn, Be)SiO_3	Yellow-white	5950	1	9	68	99	55
$CdSiO_3$	Yellow-pink	5950	2	2	30	99	45
CdB_2O_5	Pink	6150	1	2	7	92	69

division of the spectrum into eight bands,[6] and Judd's daylight duplication calculation[7] are two proposals to provide an improved criterion.

The ratio of the number of quanta of fluorescent radiation emitted to the number of quanta of exciting radiation impinging on the material is called the quantum efficiency of a phosphor. Approximate values for the quantum efficiencies may be obtained by dividing experimental luminous efficiencies* of fluorescent lamps by the maximum efficiency which might, theoretically, be obtained. The maximum possible efficiency, E_M, is given by the following equation:

$$E_M = 621\ CR \times 0.45 \times 0.90$$
$$= 251\ CR \text{ lumens per watt.}$$

C is the luminosity coefficient of the fluorescent radiation, defined by the equation $C = \int_0^\infty J_\lambda K_\lambda d\lambda / \int_0^\infty J_\lambda d\lambda$. $J_\lambda d\lambda$ is the intensity of the fluorescent radiation of wave-lengths between λ and $\lambda + d\lambda$ and K_λ is the relative luminosity. Then, 621 C is the ratio of lumens radiated to watts radiated. R is the quantum ratio, defined as the mean ratio of the energy per quantum of fluorescent radiation to the energy per quantum for the 2537 line. The quantity 0.45 is the fraction of the input wattage, to a lamp one inch in diameter and 18″ long, which is converted into 2537A. The quantity 0.90 is the estimated fraction of the fluorescent radiation which gets out of the lamp.

Experimental luminous efficiencies are quoted for the individual lamps which gave highest values, because they best indicate inherent phosphor efficiencies. The results are shown in Table III. These values are not inherent in the use of the compounds listed; on the contrary, they are markedly dependent on the purity of the constituents and on the method of preparation. Although the process of preparation differs widely for different phosphors, and each has required a long development, all these phosphors have reached quantum efficiencies between 0.53 and 0.74, and four of the six lie between 0.66 and 0.74. These values approximately have checked those on certain phosphors tested by Dr. G. R. Fonda by a completely independent method. Since quantum efficiencies of phosphors improve with a decrease in the intensity of impinging radiation and with reduction in temperature,[8] the values 0.66–0.74 may be near a limit for the conditions under which the lamps are operated. Attainment of the efficiencies quoted for fluorescent lamps

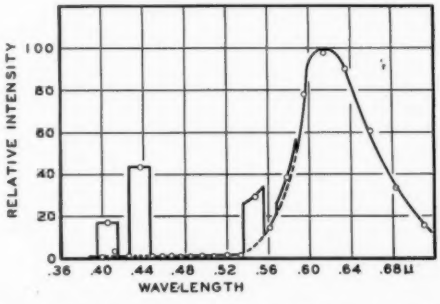

FIG. 3. Spectral distribution of visible energy radiated from a fluorescent lamp coated with CdB_2O_5 phosphor. Arc gap, 16″; tube diameter, 1″; current, 0.3 ampere.

[6] P. J. Bouma, Philips Tech. Rev. (English edition) **2**, 4 (1937).

[7] D. B. Judd, "Definition and Tolerances for Artificial Daylight for Color Matching," Paper No. 23, 1938 Optical Society of America Meeting at Niagara Falls.

* The luminous efficiencies discussed in this paragraph are those for the fluorescent radiation alone; i.e., lamp efficiencies minus the efficiency ($4lu/w$) produced by the mercury line radiation.

[8] J. T. Randall, Proc. Phys. Soc. **49**, 46 (1937).

TABLE III. *Determination of quantum efficiency of phosphors by comparison of measured with calculated luminous efficiencies of 15-watt lamps 18" long and 1" in diameter.*

PHOSPHOR	LUMINOSITY COEFFICIENT	QUANTUM RATIO	CALCULATED* LUMENS PER WATT	BEST MEASURED* LUMENS PER WATT	QUANTUM EFFICIENCY
$CaWO_4$	0.21	0.58	30	21	0.70
$MgWO_4$	.37	.53	50	35	.70
$ZnSiO_3$	.78	.48	95	70	.74
$(Zn, Be)SiO_3$	.55	.43	60	32	.53
$CdSiO_3$	.53	.42	55	30	.55
CdB_2O_5	.34	.41	35	23	.66

* Excluding mercury line radiation, which adds four lumens per watt to efficiency.

requires an optimum coating thickness of phosphor on the tube wall. A thin coat allows some 2537A radiation to be wasted, while a thick coat absorbs too much of the light.[9]

The 1931 I.C.I. system of color specification has been used for rating the color of the light from fluorescent lamps. The color ratings for the fluorescent radiation alone have been computed from spectral distribution data. The color coordinates of the light from various phosphors and from the corresponding fluorescent lamps (light from the phosphor plus light from the mercury discharge) are shown in Fig. 4. Any color point within the largest polygon which can be formed by connecting, by straight lines, the color points for the various lamps indicated on Fig. 4 may be obtained by suitable proportioning of these lamps, or by suitable mixing of phosphors within the same lamp. The latter procedure has been used to obtain two commercially available colors: warm white and daylight. Since the light from the mercury discharge affects especially the colors of lamps whose fluorescent radiation is chiefly near the long wave-length end of the visible spectrum (see Fig. 4), absorbing color coatings are required to obtain red or yellow of satisfactory purity.

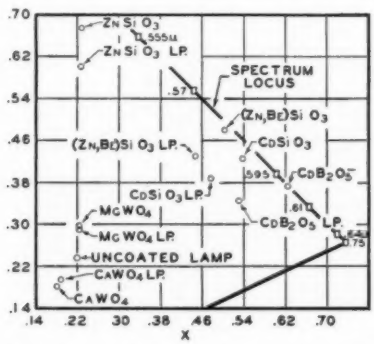

FIG. 4. Section of I.C.I. color diagram, showing the color of the light from phosphors and lamps. The color of the phosphors remains constant except that of $(Zn, Be)SiO_3$, which varies with the method of preparation.

The light from the low pressure mercury discharge is extinguished completely every half-cycle on a.c. operation, but the light from many phosphors decays slowly enough to furnish appreciable light in the interim.[10] For tungstates this decay is very rapid,[11] and the flicker of the light source is substantially the same as for the mercury discharge alone. Silicates[11] and borates, however, possess enough phosphorescence to give fluorescent lamps containing them a freedom from flicker on 60-cycle a.c. which is about as great as that for a 15-watt filament lamp. They have far greater freedom from flicker than most gaseous discharge lamps. For the same amount of brightness flicker, however, stroboscopic effects are more conspicuous in the case of a fluorescent than of a filament lamp because the former has, simultaneously, a color flicker resulting from the extinction of the mercury discharge light on a.c.[12]

[9] A. Ruttenauer and E. Blum, Das Licht **8**, 167 (1938).

[10] E. G. Andresen, Das Licht **7**, 235 (1937).

[11] T. B. Perkins and H. W. Kaufmann, Proc. Inst. Radio Eng. **23**, 1329 (1935).

[12] E. G. Andresen, Das Licht **8**, 50 (1938).

Proceedings of the Twenty-Third Annual Meeting of the Optical Society of America

NIAGARA FALLS, ONTARIO, CANADA, OCTOBER 27–29, 1938

THE twenty-third annual meeting of the Optical Society of America was held at the General Brock Hotel, Niagara Falls, Ontario, Canada, October 27–29, 1938. The meeting was opened Thursday, October 27 at 9:30 A.M. by President Gibbs.

SYMPOSIUM OF INVITED PAPERS ON THE OPTICS OF ILLUMINATION

The session Thursday morning, October 27, was devoted to a symposium of invited papers on the Optics of Illumination. The following papers were presented:

1. **Terminology and Standards.** E. C. CRITTENDEN, *National Bureau of Standards*
2. **Basic Principles Underlying the Use of Light for Illumination.** PARRY H. MOON, *Massachusetts Institute of Technology*

Widely Used Sources

3. **Oil and Gas Lamps.** WILLIAM KUNERTH, *Iowa State College*
4. **Incandescent Lamps.** E. W. BEGGS, *Westinghouse Electric and Mfg. Company*
5. **Arc Lamps.** A. C. DOWNES AND E. GREIDER, *National Carbon Company*

Recent Developments in Light Sources

6. **High Efficiency Mercury Vapor and Sodium Vapor Lamps.** L. J. BUTTOLPH, *General Electric Vapor Lamp Company*
7. **Luminescent Lamps.** RICHARD THAYER AND B. T. BARNES, *General Electric Company*

In his paper, Dr. Crittenden, former President of the Optical Society, 1932 to 1933, former President of the Illuminating Engineering Society, 1925, chairman for many years of its committee on nomenclature and standards, delegate to the International Commission on Illumination in 1924, 1928 and 1931, Councilor of the American Standards Association, and at present Assistant Director of the National Bureau of Standards, sketched the development of standard practices in the terminology of illumination, particularly through the activities during the last thirty years of the Illuminating Engineering Society whose terms and definitions published under the title "Illuminating Engineering Nomenclature and Photometric Standards" have been widely accepted as authoritative. With regard to "standards" two quite different kinds were mentioned. One includes the physical standards of measurement; the other, standards of practice and quality of products.

A new system of photometric units based upon the blackbody radiator at the freezing point of platinum as a primary standard has been adopted by the International Committee on Weights and Measures. Values for standards of light differing in color from that of the primary standard are to be established by use of the luminosity ("visibility") factors adopted in 1924 by the International Commission on Illumination. Working standards, incandescent lamps, of different types for which values have been derived from the primary standard are being compared by several national laboratories, and it is hoped that the new values of units can be introduced into practical used as of January 1, 1940.

Parry Moon, Associate Professor of Electrical Engineering at the Massachusetts Institute of Technology, author of *The Scientific Basis of Illuminating Engineering*, in his paper called attention to the fact that the branch of geometrical optics needed particularly by the illuminating engineer—that branch dealing with the calculation of illumination—has never been adequately developed and remains today in basically the same form as it was in 1760. An attempt is now being made, however, to place the subject upon a better foundation by using the concept of a vector field. One of the pioneers in this work was Hyde of the National Bureau of Standards, though most of the development can be ascribed to the Russians, Fock, Gershun, Gurevitch and Boldyrev.

The paper outlined the present status of the theory of the light field, including various methods of calculating illumination and total luminous flux. The conclusions are that the new development is of greater generality and is more closely related to the rest of physics than are the older methods. The field theory also gives three new methods of calculating illumination and two new methods of calculating flux, which may be of value in practical work.

The first of the second division papers was presented by Dr. William Kunerth, Associate Professor of Physics at the Iowa State College at Ames, and author of a *Textbook of Illumination*. This paper contained a brief resumé of the history and some of the physical characteristics of most of the important lamps depending on oil or gas as fuel. It called attention to the place these illuminants have occupied and are still supporting in the progress of lighting. They possess certain inherent advantages which have been patterned after in later developments. These illuminants have not only made it possible for people of the past centuries to make use of light in other than daylight hours, but even at the present time, they furnish an increased length of day to millions who are so situated as to be in darkness without them.

In summary, one may say that oil and gas lamps, first, have initiated a widespread movement to make the public light conscious; second, have in the main furnished light sources of low brightness; third, have given people the choice between a wide variety of illuminants; and fourth, have spurred on improvement among themselves and in the electric industry by the competition set up.

The second paper dealing with well-known sources was given by E. M. Beggs, Assistant Manager of the Commercial Engineering Department of the Westinghouse Electric and Manufacturing Company of Bloomfield, New Jersey. Points brought forward in the paper were nicely illustrated by lamps of various types which were operated at appropriate times during the lecture. The material covered the last thirty years in tungsten incandescent lamp-making. Starting with the squirted, tungsten, straight-filament vacuum 60-watt lamp of 1908 with its rated output of 475 lumens, attention was called to the subsequent increases in luminous output for the 60-watt lamp as new types were introduced and later developed. Following the initial type mentioned, there were in succession, the drawn wire straight-filament vacuum lamp, the drawn wire coiled-filament gas-filled lamp, and finally the recent drawn wire recoiled (coiled coil) filament, gas-filled lamp with its luminous output of about 825 watts. The parts played by improvements in machinery, the drawing of the wire, the coiling of the wire, the introduction of first nitrogen and later argon into the bulb of the lamp, the inside frosting and the double coiling were referred to in turn. That the 75 percent increase in lumen output of the 60-watt lamp in going from 1913 to the present is not the complete indication of the real improvement was indicated. Instead it was stated that, since the energy a lamp consumes costs about ten times as much as the lamp itself, an improvement in efficiency of 10 percent is equivalent to doubling the lamp value and that consequently tungsten lamps today are worth $7\frac{1}{2}$ times as much as thirty years ago.

The final paper on widely used sources by A. C. Downes and E. Greider was presented by Dr. A. C. Downes, director of the Research Laboratory of the National Carbon Company at Cleveland. The authors of this paper are also authors of many papers relating to carbon arcs which have been published in various journals. The characteristics, advantages and uses of the plain carbon arc, the high intensity carbon arc, and the open flame arc, colored and white were discussed.

The first paper of the third section on recently developed lamps was presented by Dr. L. J. Buttolph, Associate Director of the Research Laboratory of the General Electric Vapor Lamp Company of Hoboken, New Jersey. This paper discussed the effect of new glasses, oxide-coated electrodes and vapor pressure on the design and operation of modern high efficiency mercury and sodium lamps. Relative energy distribution, radiation output and resonance line absorption were related to operating vapor pressure as a convenient correlative of the many factors determining these radiation characteristics.

There were presented tabulated and graphic data on standardized mercury lamps ranging from the 1000-watt water-cooled quartz lamp at

75 atmospheres, efficient as a source of visible and ultraviolet, to a 15-watt air-cooled glass lamp at one-millionth of that pressure and remarkably efficient in the production of the 2537A resonance radiation.

In addition to the usual electrical and radiation characteristics, data were given on the brightness, source areas and spatial distributions.

The final paper of the symposium was presented by Mr. R. N. Thayer and Dr. B. T. Barnes of the Lamp Development Laboratory of the Incandescent Lamp Department of the General Electric Company, Nela Park, Cleveland, where the authors have had much to do with the development of the new fluorescent lamps. The causes for the great increase in luminous efficiency obtainable with the new lamps, as well as some characteristics were described as follows:

At currents in the region of 0.25 ampere in a tube 1–1½ inches in diameter containing mercury and a starting gas 60 percent of the energy input to the positive column is converted into radiant energy of wave-length 2537A. By coating the inside wall of such a tube with various synthetic phosphors whose excitation sensitivity is at or near a maximum for this wave-length, light sources of various colors can be produced at efficiencies far greater than those of incandescent filament lamps in the same colors. The daylight color produced by a mixture of phosphors in the same lamp has particular value. The after-glow of some of the phosphors gives lamps using these materials a freedom from flicker comparable to that of low wattage incandescent filament lamps. Lamps yielding different colors as well as the white lamp were demonstrated. Prospects for decoration by means of light for a reduction in glare, and for more light in the home, seem brighter.

Visits to the University of Buffalo and the Plant of the Spencer Lens Company

Thursday afternoon was spent in a visit to the University of Buffalo and to the plant of the Spencer Lens Company. At the University of Buffalo the laboratories were opened for inspection. At the Spencer Lens Company plant small parties were taken around the shops where they saw the various steps in manufacture of precision optical instruments.

Dinner at the Park Country Club

After the visit to the shops the Spencer Lens Company entertained the members and their guests with a dinner at the Park Country Club.

Popular Talks and Lecture

Following the excellent dinner, short interesting talks were given by H. N. Ott, President of the Spencer Lens Company and B. H. Witherspoon, Vice President. Their subjects were, "Scientific Optical Instruments: Reminiscences and Prophecy," and "Scientific Optical Instruments: Their Development in America and Europe." There followed an instructive entertaining lecture by I. G. Reimann, Curator of Geology, Buffalo Museum of Science on the Geology of the Niagara Region.

Sightseeing Trip

Friday afternoon members of the society visited the Cyanamid plant, the Queenstown Power House, the Rapids, the Whirlpool, Brock's Monument, the Welland Ship Canal and the Locks at Thorold, returning in time for the annual dinner at 6:30 P.M.

Lecture by Dr. McMath

Friday evening following the annual dinner at the General Brock Hotel, an unusually entertaining and instructive lecture was given by Dr. Robert R. McMath, Director of the McMath-Hulbert Observatory of The University of Michigan, at Lake Angelus, on the subject, "Eruptive Solar Prominences." The lecture was accompanied by excellent motion pictures, the first of their kind to illustrate the subject matter.

The apparatus used for this study is a development of the spectroheliograph designed to make motion picture records of the rapidly changing solar phenomena as seen on the sun's disk or extending out beyond its edge into the adjacent space.

Most of these pictures were taken with the light from the K_2 line of Ca^+ or the H alpha line of hydrogen. In order to insure a true and com-

plete picture of the prominences, the spectrograph slits were widened sufficiently to include most of the line distortions caused by the Doppler effect of radial velocity. The rate of photography is much less than that of projection which fact permits showing, in a few minutes on the screen, the developments recorded in several hours. The outer surface of the sun was shown to be in constant turbulence, seething like the surface of some molten mass in a gigantic cauldron. Many different types of prominences were shown in action, some like flames bursting from the surface were feeding streamers along curved paths back into a center of attraction, some hanging like great glowing detached clouds were dropping knots of bright material and long "fiery" filaments thousands of miles back to the surface and others lifted slowly from the sun, moved upward steadily for a period and then rushed off into space at tremendous velocities. Very interesting was the statement that all this moving material proves to have a succession of *uniform* velocities and that the change from one velocity to the next is apparently instantaneous.

Business Session

A brief business session of the Society was held Saturday morning, October 29 at 9:30 A.M. President Gibbs presided. Formal reports of the Secretary, Editor-of-Publications and Treasurer for the calendar year 1937 were laid before the Society. The reports were supplemented by informal reports of the changes since January 1, 1937.

The Secretary then laid before the Society the report of the Nominating Committee nominating A. G. Worthing to succeed himself as Director-at-Large for a term to end in October 1939, noting that the members of the Society had been duly notified of this nomination and that no further nominations had been received. The Society voted that the Secretary be instructed to cast an unanimous ballot for A. G. Worthing. President Gibbs then declared A. G. Worthing elected.

Votes of thanks were given to the University of Buffalo, the Spencer Lens Company and the manager of the General Brock Hotel and the Secretary was instructed to notify them of this action.

Contributed Papers

Sessions for the reading and discussion of contributed papers were held Friday, October 28, at 9:30 A.M. and Saturday, October 29, at 10:00 A.M. The authors' abstracts of these papers are appended.

Registration

Members 69, Guests 27, Total 96.

Meeting of the Board of Directors

A meeting of the Board of Directors was held on Wednesday, October 26, 1938. Minutes of the meeting are appended.

L. B. Tuckerman, *Secretary.*

Minutes of the Twelfth Meeting of the Directors of the Optical Society of America, Incorporated

General Brock Hotel, Niagara Falls, Ontario, Canada, October 26, 1938

BESIDES the transaction of routine business, the following items of general interest to members of the Society were taken up.

Membership

The Secretary's report showed that since January 1, 1938 the membership had increased from 624 to 649 and that since the last meeting of the Directors 16 new members had been elected as of January 1, 1938 and 9 new members as of January 1, 1939.

The Secretary reported there had been one death among the membership since the February meeting.

Transfer from Associate to Regular Membership

The following were transferred from associate to regular membership:

James F. Angier	(972)
Frank T. Avignone, Jr.	(1108)
Stanley S. Ballard	(1126)
William Feinbloom	(1137)
Isidore S. Finkelstein	(1107)
Paul C. Foote	(1105)
Walter W. Graeper	(1111)
Frederick W. Jobe	(1102)
Harry J. Keegan	(1128)
Kenneth L. Kelly	(1129)
Victor R. Knop	(1104)
John R. Loofbourow	(1134)
L. C. Martin	(1113)
Alfred H. Parsons	(1119)
Wm. M. Preston	(1131)
Seymour Rosin	(1103)
Ray P. Teele	(609)
Michael J. Zigler	(1136)

Financial Status of the Society

The Treasurer gave an informal report which showed that the Society had maintained its excellent financial condition.

Election of Representatives on Inter-Society Color Council

The following were elected as representatives of the Optical Society of America on the Inter-Society Color Council for a term to expire in October, 1940:

I. H. Godlove, *Chairman*	voting delegate
L. A. Jones	voting delegate
D. B. Judd	voting delegate
J. W. Forrest	
H. P. Gage	
A. C. Hardy	
W. B. VanArsdel	

Nomination of Representative on the Governing Board of the American Institute of Physics

The nomination of W. B. Rayton to succeed himself as representative on the Governing Board of the American Institute of Physics for a term to end February, 1942, was approved.

American Standards Association Committee on Photography

It was voted that the Optical Society of America accept sponsorship for an American Standards Association Committee Z-38, Photography with the following scope of activities:

"The formulation of definitions, dimensional standards, and recommended practices in the field of photography, and the establishment of methods for testing, rating and classifying the performance characteristics of materials and devices used in photography, including its industrial applications but excluding cinematography."

Placement Service Committee Representative on American Institute of Physics Committee

The Board of Directors appointed President Gibbs to represent the Optical Society of America on the Placement Service Committee of the American Institute of Physics.

Joint Meeting in February, 1939

It was voted that, subject to approval, the meeting in February be a joint meeting with the American Physical Society, the Inter-Society Color Council and the Optical Society of America, to be held in New York.

Annual Meeting

It was voted that the annual meeting of the Society be held at the Lake Placid Club, New York on October 12–14, 1939 providing suitable arrangements could be made.

L. B. Tuckerman, *Secretary.*

Optical Society of America, Incorporated

Notice of Election of Officers

IN accordance with Article III, Section 6 of the By-Laws of the Optical Society of America the following officers and directors are to be elected at or before the Annual Meeting in October 1939:

President, Vice President } for a term of two years
2 Members-at-large of the Board of Directors for a term of four years.

The present officers are:

	Term Expires at Annual Meeting in
President—R. C. Gibbs	1939
Vice President—K. S. Gibson	1939
Secretary—L. B. Tuckerman	1941
Treasurer—Henry F. Kurtz	1941
Past President—A. C. Hardy	1939
Editor—F. K. Richtmyer (elected by Directors)	1941
Directors-at-Large:	
G. R. Harrison	1939
A. G. Worthing	1939
H. P. Gage	1941
W. F. Meggers	1941
Brian O'Brien	1941

In accordance with the By-Laws, Article III, Section 4:

> "No member at large of the board of directors shall be eligible for reelection."

G. R. Harrison and A. G. Worthing are not eligible for reelection.

The following Committee on Nominations has been appointed and confirmed in accordance with Article III, Section 6 of the By-Laws:

Arthur C. Hardy, *Chairman*,
Massachusetts Institute of Technology,
Cambridge 39, Massachusetts.
Fred E. Altman,
Hawk-eye Works, Eastman Kodak Company,
Rochester, New York.
Frank Benford,
Research Laboratory, General Electric Company,
Schenectady, New York.
I. C. Gardner,
National Bureau of Standards,
Washington, D. C.
Brian O'Brien,
University of Rochester,
Rochester, New York.

It will be the duty of this committee to make nominations for the above-mentioned election. The Committee report is to be made not later than July 15, 1939.

Although, after the committee has made its report, an opportunity will be given for additional nominations by petition, members are urged, as soon as possible, to suggest names which should be considered by the committee. Suggestions may be sent to the Chairman or any other member of the Committee.

Only regular and honorary members are eligible to election. A list of members, officers and past officers was published in the J. Opt. Soc. Am. Vol. 28, No. 6, pp. 190–208, June, 1938. [Later transfers to regular membership are given in the Minutes of the Twelfth Meeting of the Directors of the Optical Society of America, Incorporated, held October 26, 1938 and published on p. 138 of this number of the Journal.]

L. B. Tuckerman, *Secretary*.

Program of Sessions for Contributed Papers

(Titles and Abstracts of Papers)

1. Experiments on Optical Rotation of Unpolarized Light. F. A. Molby, *West Virginia University*. (15 minutes.)

An experiment will be described which corroborates the results found by Langsdorf and DuBridge,[1] that optically active substances produce observable effects upon unpolarized light. This experiment is not thought to contradict the conclusion reached by Birge[2] that such experiments do not tell us of the nature of unpolarized light. Like the experiment of L. and D., it can be explained and its results predicted upon the assumption of elementary light components which are plane polarized. Essentially the experiment consists in placing a biquartz on a hinged mounting over the collimator lens of a spectroscope in such a way that it can be tilted out and into place to uncover or to cover a lens aperture which has been arranged to produce

a spectrum crossed by Talbot's bands, and observing and photographing the effect of the biquartz upon the Talbot band system in the visible range of the spectrum. Biquartz of 3.8 mm thickness and 7.6 mm thickness have been used, producing rotatory dispersion sufficient to permit observation of several regions in the spectrum at which the respective light vectors are recombined at multiples of 90 degrees orientation.[3] At 90 degrees, 270 degrees, etc. the Talbot bands disappear. At 180 degrees complementary Talbot bands appear. At 360 degrees, Talbot bands appear identically as when the biquartz is removed, their location being noted by a crosshair and eyepiece fixed to travel across the focal plane of the spectrographic camera. Observed results will be mentioned for polarized incident light as well as for unpolarized incident light.

[1] Alexander Langsdorf, Jr. and Lee A. DuBridge, J. O. S. A. **24**, 1 (1934).
[2] Raymond T. Birge, J. O. S. A. **25**, 179 (1935).
[3] One half of the light having traversed right quartz while the other half of the light traversed left quartz.

2. The Colors of Mosaic Powder Films.* A. H. PFUND, *Johns Hopkins University.* (10 minutes.)

A mosaic powder film consists of a single layer of white pigment particles (ZnS, TiO_2, etc.) spread on a glass surface. Discrete, small areas contain closely crowded pigment particles while adjacent areas are pigment free. Under proper conditions, such films will show brilliant colors in transmitted light. These phenomena are studied by means of spectral transmission, in the visible and near infra-red spectrum. The transmission curve for a given mosaic film shows a marked minimum which vanishes completely when the particles are dispersed. It is shown (1) that the mosaic structure is essential to the appearance of the transmission minimum, (2) that the wave-length of the minimum moves to greater wave-lengths as the particle-size increases, (3) that the position of the minimum shifts to shorter wave-lengths upon covering the mosaic film with a medium of higher refractive index. Two possible explanations of the transmission minima are considered: (1) The Schwarzschild-Debye theory of scattering, (2) the simple interference theory (colors of mixed plates). The latter explanation is favored. It is finally pointed out that when a suitable technique for the production of reproducible films shall have been worked out, it will be possible to evaluate particle-size, refractive index and particle-size distribution.

* The present paper will appear in full in J. O. S. A.

3. An Experimental Study of Some Effects of Temperature and Exposure to X-Rays and Cathode Rays upon Triboluminescence.* FRANCES G. WICK, *Vassar College.* (10 minutes.)

Previous observations[1, 2] have shown that the triboluminescence of fluorite and some other natural and synthetic materials is greatly increased in intensity by exposure to radium. The spectrum of this triboluminescence is the same as that of the phosphorescence and low temperature thermoluminescence observed in the same specimens. Other substances examined show no change in intensity due to exposure to radium. The effects of exposure to x-rays and cathode rays are similar to those of exposure to radium. The intensity of triboluminescence of some specimens is intensified and shows definite relation to phosphorescence and thermoluminescence. That of other specimens is not changed. In a number of specimens including the fluorites phosphorescence of different colors through different temperature ranges was observed after exposure to x-rays at liquid-air temperature. Corresponding triboluminescence of the same color was observed at a lower temperature than that at which the phosphorescence is emitted, further verifying the relation of triboluminescence to phosphorescence. The effect of temperature upon the triboluminescence of a large number of specimens was observed by grinding the materials in a mortar at room temperature, at liquid-air temperature and at 60°C. One group of these substances including quartz and uranium nitrate shows marked increase of intensity as the temperature is lowered and decrease as the temperature is raised. Another group including fluorite and other specimens which are phosphorescent after exposure to x-rays shows little or no triboluminescence at the lowest temperature and either increased intensity as the temperature is raised to the highest temperature or maxima at intermediate temperatures. Another group including sphalerite shows no change in intensity with change in temperature.

* The present paper will be submitted in full to the J. O. S. A. for publication.
[1] Frances G. Wick, J. O. S. A. **27**, 275 (1937).
[2] Frances G. Wick, Mitt. d. Inst. f. Radiumforschung No. 389, Wien. Ber. 11a, **145**, 689 (1936).

4. A Simplified Derivation of the General Properties of an Electron-Optical Image.* E. G. RAMBERG, *Radio Corporation of America.* (Introduced by L. B. Tuckerman.) (10 minutes.)

The image forming property and the form of the Seidel aberrations of an axially symmetric electric and magnetic field are derived as far as possible with the aid of symmetry considerations (and Larmor's theorem) only. To remove the remaining indefiniteness with regard to the coma angle and the eccentricity of the ellipse of magnetic astigmatism it becomes necessary to make use of existence of the wave surfaces associated with the electron pencils.

* The present paper will appear in full in J. O. S. A.

5. An Automatic Recording Spectrophotometer for Cathodoluminescent Materials. V. K. ZWORYKIN, *RCA Manufacturing Company.* (Introduced by L. B. Tuckerman.) (10 minutes.)

An automatic recording spectrophotometer for the visible, especially adapted for the study of cathodoluminescent materials, is described. It consists of a demountable light source and an interrupter, a glass monochromator with compensation for the variation of the dispersion with wave-length, a photoelectric electron multiplier, a signal amplifier stabilized by negative feedback, and a motor drive amplifier controlling the deflection of the recording head. The wave-length scale is made linear by the introduction of a spiral cam of appropriate form. The system is distinguished by high sensitivity (usable for sources emitting 1 millilumen/cm^2), high speed ($1\frac{1}{4}$ minutes for a record), linear wave-length scale, high stability and easy adjustment.

6. Absorption and Emission Spectra of Luminescent Materials Used in Kinescopes.* HUMBOLDT W. LEVERENZ AND ELTON J. WOOD, *Radio Corporation of America.* (Introduced by L. B. Tuckerman.) (10 minutes.)

Relative spectral energy distributions and visual stimulation curves are given for the more efficient crystalline luminescent materials (phosphors) used in television cathode-ray tubes (kinescopes). Color, brightness and efficiency characteristics are discussed. Sixteen phosphors, having emission colors ranging from violet to red and including purples and white, are to be demonstrated.

* The present paper will appear in full in J. O. S. A.

7. Photographic Film Speeds as Evaluated in Terms of Print Quality.* LOYD A. JONES, *Kodak Research Laboratories.* (30 minutes.)

It seems quite certain that the information the user of a photographic negative material, particularly amateur, wishes to have about its sensitivity is how little exposure he can give and still obtain a *good print.* The negative itself is only a means to an end and it makes little difference what its characteristics are provided a print of satisfactory quality can be made therefrom. It seems justifiable to conclude that the most satisfactory evaluation of *effective camera speeds* should be based on the *minimum* exposure which will yield negatives from which prints of satisfactory quality can be made. A statistical study has been made of the relation between print quality and negative exposure. A series of prints made from negatives obtained by using a group of typical amateur negative materials has been subjected to the judgment of 200 observers. The results show a very satisfactory degree of agreement on the magnitude of minimum exposure required to produce a negative from which an *excellent* print can be made. Such a method constitutes a satisfactory though cumbersome method of evaluating the effective camera speed of a negative material. By a careful analysis of the tone reproduction characteristics of this excellent print, as determined by purely sensitometric measurements, a method has been found whereby the desired information can be deduced directly from sensitometric measurements alone, thus making it unnecessary to go through the lengthy and laborious process of the statistical method mentioned above. The *criterion* of effective camera speeds thus established is based upon the gradient of the density-log exposure characteristic of the negative material rather than upon inertia or density. From the standpoint of tone reproduction theory, the ability of a photographic material to reproduce the brightness differences of an original is most significantly represented by gradient and hence such a criterion seems to be of maximal significance for the expression of effective camera speeds.

* The present paper will appear in full in J. O. S. A.

8. The Accuracy Requirements in a Fifth Place Refractometer and an Instrument Meeting these Requirements. J. W. FORREST AND H. W. STRAAT, *Bausch & Lomb Optical Co.* (20 minutes.)

If one is to do fifth-place refractometry with a prism type instrument, the working parts of the unit, whether optical or mechanical, must be designed and maintained with a very high degree of accuracy. There is practically a one-to-one correspondence between accuracy of reading in the fifth decimal place and prism index in the fifth decimal place. In practice we may compensate a prism index error of small magnitude by altering prism angle but this will leave plus and minus residual errors which we must hold within our prescribed tolerance. With an accurately designed optical system we must combine a scale system and an operating mechanism which will enable us to utilize its full precision. We must also take into consideration factors external to the system itself, the most important of these being temperature control. It is useless to design a refractometer for liquids with an accuracy so great that we cannot control our temperature sufficiently well to make good use of it. Each of the standard classical types of prism refractometer has inherent advantages and faults. It is possible to design a unit in which the advantages are retained and the faults eliminated. Such a unit has been successfully designed and manufactured and is briefly described. Compensating Amici prism systems and their attendant errors are eliminated by the use of the sodium Lab-Arc, in place of white light. The instrument has two ranges, from 1.33 to 1.48 and from 1.40 to 1.70, and is calibrated for the *C* and *F* lines of hydrogen as well as for sodium. The scale is of the equi-division type and read by vernier. To increase bearing accuracy, the entire unit has been arranged mechanically so that the bearing is vertical as in a transit or precision spectrometer.

9. Some Useful Formulae for Optical Calculation. MAX HERZBERGER, *Eastman Kodak Co.* (15 minutes.)

It is suggested that the centers of the different surfaces be taken as reference points, instead of the vertices. The labor of calculation will then be reduced even for the ordinary paraxial and meridional ray tracing. This reduction becomes very considerable if we transform the calculation of meridional astigmatism to this scheme, and it becomes almost indispensable if we try to solve the very important problem of coefficients; that is, to study the effect of small changes in radii, thicknesses, and refractive indices upon the position of the emergent rays. The geometrical idea of the new method is sketched, and the more important of the formulae given.

10. The Inter-Society Color Council Tentative System of Color Names. DEANE B. JUDD.* *National Bureau of Standards.* (20 minutes.)

The system of color names was worked out within the Council at the request of the American Pharmaceutical Association for the purpose of designating colors in the U. S. Pharmacopoeia, in the National Formulary, and in general pharmaceutical literature. The general plan was worked out in 1932,[1] the hue names and modifiers from which the color names are to be composed were adopted in 1937 and the selection of the boundaries defining the groups of colors to be known by the 320 names is now in process of examination by the Council delegates in what it is hoped will be the final review before formal adoption.

The system is based upon the arrangement of surface colors in a tridimensional figure known as the color solid; this solid is divided into 320 approximately equal compartments, whose colors are to be known by the same name. The hue names for dark colors include compounds of brown and olive; those for light colors, compounds of pink. The adjectives, strong and weak, indicate variations in saturation; and the adjectives, light and dark, those in lightness or value. The adjectives, pale, deep, dusky and brilliant, indicate departures from the typical (medium, moderate) colors of each hue involving both lightness and saturation. The Munsell color system has been used as an aid in the selection of boundaries between the various groups of colors, and these boundaries are for the present tentatively specified in Munsell terms only. When final boundaries have been selected it may be worth while to translate them to fundamental tristimulus terms. The translation into the new system of 600 of the most important of the colors shown in the Maerz and Paul *Dictionary of Color* and of 300 of the most important colors standardized by the Textile Color Card Association of America is under way, and the suitability of the new names found is one means of testing the adequacy of the proposed system. The names of the tentative system have been chosen to apply particularly to the colors of matte, opaque surfaces; revisions required to make the system applicable to the colors of transparent media will be discussed.

* O. S. A. delegate to the Council, Chairman of the Council Committee on Color Problems.
[1] I. H. Godlove, Report of the Committee on Measurement and Specification, Bulletin No. 1, Inter-Society Color Council, June 7, 1932.

11. An Experimental Determination of the Spectral Location of the Psychologically Unique Colors.* MARGARET R. HUBBARD AND FORREST L. DIMMICK, *Hobart College*. (15 minutes.)

Seven points of reference, combined in an equation of four terms, have been proposed[1] as necessary and sufficient for the psychological description of all colors. Standards for black and white have been fairly well established, and a standard middle gray has been specified experimentally. When we seek comparable standards for the remaining primary colors, however, we do not meet with similar success.[2] We find a large amount of data, little of it substantiating any part of the remainder, data obtained by different methods, on different assumptions, and for different purposes. The question of the principal or unique colors has not been attacked from a single experimental concept and with a controlled psychological methodology. We undertook such an investigation. Using monochromatic stimuli, we determined the limits of the regions of yellow, of green and of blue. All spectral reds proved to be yellowish. Care was taken to eliminate the psychological objections to the work of earlier experimenters. The combined results of 10 observers give 583$\mu\mu$ for the middle of the yellow region, 515$\mu\mu$ for the green, and 476$\mu\mu$ for the middle of the blue. Spectral red plus a measured amount of the above blue gives an unique red. With these unique colors as standards, it is possible to specify a color with reference to three noncomplementaries and gray in such a way that the specification indicates the psychological appearance of the color, (R or G)+(B or Y)+(Bk or W)+G=C. At the same time, translation can be made readily to the physical 3-color notation.

* The present paper will appear in full in American Journal of Psychology.
[1] F. L. Dimmick, "A Reinterpretation of the Color Pyramid," Psychol. Rev. **36**, 83–90 (1929).
[2] D. B. Judd, "Hues of the Spectrum Colors," Natl. Bur. Stand. LC–454, 1935.

12. A Four-Filter Photoelectric Colorimeter. B. T. BARNES, *General Electric Company*. (10 minutes.)

In this instrument, G. E. lightmeter cells equipped with glass filters give a close approximation to the I. C. I. color rating of any source. The X response for radiation of wave-lengths less than 0.504μ is obtained with a separate cell-filter combination. This cell is connected in parallel with the two cells which give the X response for radiation of wave-lengths greater than 0.504μ. Diaphragms placed in front of certain cells are adjusted until the three meter readings obtained with each source are, as nearly as possible, proportional to the I. C. I. color coordinates for the source. Tests of fluorescent lamps of seven different colors gave differences between true and instrumental color coordinates ranging up to 0.010. Deviations from a standard color caused by minor variations in spectral distribution can be measured with much greater accuracy. Photometric ratings of fluorescent lamps of the seven standard types with this instrument gave errors ranging up to 3 percent, unless a separate calibration factor was used for each color. Filter changes are suggested which would make the instrument more accurate. The filters specified below are the best found to date. The cells for use with the X filter for λ's$>$0.504μ and with the Y filter must be selected to have the right sensitivity variation in the range 0.58 to 0.68μ.

FILTER	GLASS* NUMBER	MELT NUMBER	THICKNESS (mm)	CELLS NEEDED
X (λ's$>$0.504μ)	330	11–9–31	9.5	2.00
	397	11–19–35	3.48	
Y	330	11–9–31	3.35	0.9
	428	7–20–35	2.85	
Z	GG3	26744	0.45	0.9
	554	2–13–35	2.60	
	555	2–7–36	3.80	
	038†			
X (λ's$<$0.504μ)	GG3	26744	0.45	0.25
	554	2–13–35	5.20	
	555	2–7–36	5.95	
	038†			

* Corning glasses, except for Jena GG3.
† Corning No. 038 samples to have 52 percent transmission for λ0.415μ.

13. A High Speed Device for Absorption Spectrophotometry. GEORGE R. HARRISON, *Massachusetts Institute of Technology*. (15 minutes.)

Tests have been carried out on the component parts of a new device designed for automatic high speed absorption spectrophotometry in the range 2000 to 10,000A. This involves use of five techniques which have not been applied previously to absorption or reflection measurements: (1) Use of a concave diffraction grating monochromator of

new design. This is made practicable by the aluminized gratings of R. W. Wood, and an instrument has been constructed which gives complete coverage of the range desired with almost uniform dispersion, in a single instrument with a simple optical system. Light of high spectral purity and ample intensity for photoelectric measurements is obtained. (2) Use of an electron multiplier photocell, thus reducing amplification difficulties and increasing speed, sensitivity, and stability. (3) Cathode-ray tube indication of and continuous film recording of extinction coefficients or densities directly, giving high speed response and recording of 20 measurements per second. 2000 measurements over an 8000A range can thus be made in 100 sec. (4) Use of an electrically driven oscillating quartz mirror for shifting the measuring beam of monochromatic light from solution cell to blank cell. (5) Use of a new scanning method of photometric balance which gives the advantages of both direct-reading and null methods. The system calibrates its own electrical response 20 times per second, and its optical response is essentially neutral. Precision to 1 percent is expected, which is superior to that of photographic methods and ample for most purposes of absorption spectrophotometry other than those involving color determination. Results can be obtained either as photographed curves, or as photographed tables, of any desired function of wave-length and density.

14. An Improved Luminosity Filter. KASSON S. GIBSON, RAY P. TEELE AND HARRY J. KEEGAN, *National Bureau Of Standards.* (15 minutes.)

A new luminosity filter was described at the last meeting of the Society. In the abstract[1] it was noted that the principal defect of the filter was the nonreproducibility of the special Corning G34 glass. The remaining stock of this glass has proved unsatisfactory. Other means of reproducing the standard I. C. I. luminosity curve below 520 mμ have, therefore, been sought. A combination of a potassium dichromate solution and a uranium glass has resulted in about the same degree of duplication of the short wave luminosity data as before, and has proved superior in practical tests of the complete filter. The uranium glass appears sufficiently reproducible, judging from spectral transmission measurements made on three different melts, two fluorescent and one (relatively) nonfluorescent. The composition of the complete filter is tentatively as follows: 1. *Solution:* $CuSO_4 \cdot 5H_2O$, 20.00 grams; $CoSO_4(NH_4)_2SO_4 \cdot 6H_2O$, 2.05 grams; $K_2Cr_2O_7$, 0.150 grams; H_2SO_4 (sp. gr. 1.835), 10 ml; H_2O, distilled, to make one liter of solution. 2. *Glass:* Uranium (canary), Corning No. 375 or equivalent, transmission at 486 mμ equal to 0.40 ± 0.01. The solution must be used in a cell of 5.00 cm length, which must be placed between the illuminant and the uranium glass (to reduce fluorescence of the latter). A slight amount of infra-red energy is transmitted; this extends from 850 to 1200 mμ (maximum transmission about ½ percent at 1090 mμ) and amounts to 1 or 2 percent of the total energy transmitted by the filter from an incandescent lamp. It may be evaluated by means of an infra-red filter and the correction should be made for the most accurate results. The above filter composition is subject to possible small revision; furthermore, search is being made for a yellow solution which would eliminate the need for the uranium glass, but this is as yet unsuccessful. In the meantime the luminous transmissions of highly selective railroad signal glasses, measured on the physical photometer with the above filter, agree so closely with those computed from spectral transmission data on the glasses, using the standard I. C. I. luminosity data, that it seems advisable to make the information available for those interested.

[1] J. O. S. A. **28**, 178 (1938).

15. Definition of Artificial Daylight. DEANE B. JUDD,* *National Bureau of Standards.* (20 minutes.)

The International Commission on Illumination through its Secretariat Committee (No. 27) for "Natural and Artificial Daylight"[1] has undertaken to prepare a definition of artificial daylight suited to practical purposes. As a first step they have circulated to the several National Committees on Illumination a questionnaire translated as follows: (1) Shall the chromaticity of artificial daylight correspond to that of standard illuminant *B* of the colorimetry committee, which has already been standardized as artificial daylight by the I. C. I., or is another definition of artificial daylight desired in terms of the color triangle? (2) Since the location of the point in the color triangle is not sufficient for defining the color effect of artificial daylight, then basically it is necessary to have the spectral-energy distribution for a source of artificial daylight. Various procedures are available. (*a*) According to Richter[2] certain regions of the spectrum are chosen and in these regions the relative amounts of artificial and natural daylight are compared with each other. The differences between the two should not exceed some certain value still to be defined. This has to do, as in the following, solely with the basic definition of method and not with such details as the number of steps in the spectra, which are to be compared with each other, and tolerances for the comparisons. (*b*) According to Bouma,[3] the colors of the samples of an Ostwald hue circle or of some other hue circle are compared under natural and artificial daylight with each other and in doing so it is observed by how many color steps the samples change if a change is made from one light source to the other. Do you have any practical experience with these two methods and can you state which of these methods, or both, or a third, would be suitable for a definition of artificial daylight? (3) Since on physiological grounds an essential role is played by the amount of illumination supplied by the source of artificial daylight it would be desirable if the illumination by artificial daylight approximated that by natural daylight in order to avoid the impression of insufficient illumination. Are you agreed that on these grounds a minimum illumination of $E = 1000$ lux (about 90 footcandles) be prescribed for artificial daylight at the working plane? (4) Sufficient illumination granted, can the mixture of incandescent lamp light and mercury vapor light in 1 to 1 proportion of luminous flux be designated as satisfactory, or is another proportion required, or the definition of several proportions for different purposes? Tentative replies to these

questions, intended to represent American practice and opinion, will be given and discussed. Written comment on these questions is solicited from those having information that should be taken into account in formulation of the final replies.

* U. S. Representative for Artificial Daylight.
[1] Formerly Austrian, now German Secretariat Committee.
[2] Das Licht, **6**, 223, 251 (1936).
[3] Philips Tech. Rev. **2**, 1 (1937).

16. Definition and Tolerances for Artificial Daylight for Color Matching. DEANE B. JUDD, *National Bureau of Standards.* (15 minutes.)

The method of defining artificial daylight is based upon the principle of preserving object-color differences; that is, if one of two samples appears just noticeably redder than the other in natural daylight it should also appear just noticeably redder under the artificial illuminant, and if the one illuminant shows an object-color difference to be zero, the other should also yield a color match. This principle has been applied to a number of artificial sources by computation based on spectral-energy distributions. The 1931 I. C. I. standard observer[1] and the uniform-chromaticity-scale coordinate system[2] have been used. Four pairs of samples have been chosen to typify those known to require accurate duplication of daylight. No standard of natural daylight has been chosen, but computations have been carried out for I. C. I. standard illuminants *B* and *C*, and six other possible choices. The method is to compute from spectrophotometric data the trilinear coordinates (r, g, b) and apparent reflectance (A) for the eight samples both for natural daylight and the artificial illuminant. Let the subscripts p and q refer to the samples of each pair; then each object-color difference may be characterized by the three first differences:

$$\Delta_1 r \equiv r_p - r_q, \quad \Delta_1 g \equiv g_p - g_q, \quad \Delta_1 L \equiv k(A_p^{\frac{1}{3}} - A_q^{\frac{1}{3}}),$$

where $\Delta_1 r$ and $\Delta_1 g$ taken together indicate the character and amount of the chromaticity difference between the samples, $\Delta_1 L$ is the lightness difference, and k is a constant (about 0.2) which adjusts the indications of lightness and chromaticity to a comparable basis. Let the subscripts a and n refer, respectively, to the artificial illuminant and natural daylight; then the degree to which the one fails to duplicate the other is indicated for each object-color difference approximately by the largest of the second differences:

$$\Delta_2 r \equiv (\Delta_1 r)_a - (\Delta_1 r)_n, \quad \Delta_2 g \equiv (\Delta_1 g)_a - (\Delta_1 g)_n,$$
$$\Delta_2 L \equiv (\Delta_1 L)_a - (\Delta_1 L)_n.$$

Granted that the four pairs of samples adequately typify those to be examined under the artificial illuminant, then an average of the four largest second differences is an adequate measure of the failure of the artificial illuminant to duplicate natural daylight, and a value of this average may be set as a tolerance.

[1] J. O. S. A. **23**, 359 (1933).
[2] J. O. S. A. **25**, 24 (1935).

17. Artificial Daylighting for Color Grading of Agricultural Products.* DOROTHY NICKERSON, *Bureau of Agricultural Economics.* (15 minutes.)

Color is an important quality factor in many agricultural products, and favorable conditions of illumination are therefore necessary for grading these products. Preferred natural conditions are described. It is not always possible to make these conditions available, nor is the illumination stable even when such conditions are available. Specifications for artificial daylighting have therefore been developed. On the basis of studies made in cotton classification rooms these require: (1) diffuse illumination, (2) color to match a slightly overcast north sky, (3) intensity about 60–80 footcandles when nearby wall color is a neutral gray about Munsell 7/. A satisfactory source-and-filter combination developed for use in the Bureau of Agricultural Economics color laboratory is described. A trial made of illumination at 6500°K found the illumination was too yellow, flattering the creamy color of the cottons. The color temperature finally adopted as satisfactory is about 7400°K. The intensities at table height are about 100 footcandles with 1000-watt lamps, 50 footcandles with 500-watt lamps. The final installation includes 500-watt lamps in the center group, with 1000-watt lamps on the ends. Energy distribution and color temperature data are given for certain daylight standards, for the unit developed, and for other sources of artificial daylight.

* The present paper will be submitted to the *Journal of the Optical Society of America.*

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